Annual rhythms in the daily movement behaviours of Australian adults

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Abbreviations

ARIA	Annual Rhythms In Adults' lifestyle and health study
AUD	Australian dollar
BMI	Body mass index
CI	Confidence interval
COVID-19	Coronavirus disease 2019
DASS-21	Depression Anxiety Stress Scale
DST	Daylight saving time
DQES	Dietary Questionnaire for Epidemiological Studies
HABITAT	How Areas in Brisbane Influence Health and Activity
hPa	Atmospheric pressure
ICC	Intraclass correlation coefficient
Int$	International dollar
JBI	Joanna Briggs Institute
LPA	Light physical activity
METs	Metabolic equivalents
MVPA	Moderate-to-vigorous physical activity
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SB	Sedentary behaviour
SD	Standard deviation
SMD	Standardised mean difference
USD	United States dollar
WMD	Weighted mean difference
WHO	World Health Organisation
WHOQOL-BREF	World Health Organization Quality of Life assessment 26-item version

Summary

Within a 24-hour day, time is distributed across three broad movement-related behaviours: sleep, sedentary behaviour and physical activity. Each of these behaviours are associated with health and wellbeing outcomes. The daily spread of time across behaviours has potential to vary widely day-to-day, yet little is known about the temporal natural of daily movement behaviour patterns. This knowledge gap is a product of the limitations in previous data collection methods and studies exploring behaviours in isolation. Recent advances in wearable activity tracker technology allows for device-measured 24-hour data to be captured in a relatively cost-effective and hands-off way. This thesis aims to contribute to the current body of literature on movement-related behaviours by exploring the temporal patterns in daily movement behaviours through four original studies.

The opening chapter introduces the temporal context of year-long movement-related behaviour patterns. Additionally, this chapter describes the associations between movement-related behaviours and health and wellbeing, measurement options for capturing 24-hour movement, movement guidelines, prevalence of meeting guidelines, and secular trends of movement-related behaviours.

Chapter 2 (original study 1) is a systematic review and meta-analysis exploring current literature on annual temporal patterns of movement-related behaviours. Temporal events included in the review are seasonal changes, observance of Ramadan, vacations, and daylight savings time transitions.

Next, Chapter 3 describes the methodology of the Annual Rhythms In Adults' Lifestyle and Health (ARIA) study. ARIA explored the intra-year patterns of body weight, movement-related behaviours, diet, mental health, wellbeing and lifestyle in a cohort of 375 Australian adults. ARIA collected 13 months of continuously measured minute-by-minute movement-related behaviour data via Fitbit wearable activity trackers. These data are the primary sources of data used in the remaining three studies in this thesis. This chapter concludes with a detailed description of my unique contribution to the conduct of ARIA.

Chapter 4 (original study 2) is a cohort study on the annual rhythms in movement-related behaviours of Australian adults (ARIA study participants). Year-long patterns are described along with exploration of intra-annual temporal cycles (i.e. day of the week, seasonal) and temporal events (i.e. Christmas-New Year period, daylight savings time transitions) and their associations with movement-related behaviours. Associations are explored using multi-level mixed-effects linear regression models.

Chapter 5 (original study 3) explores the association between movement-related behaviours of Australian adults (ARIA study) and weather variables. Specifically, daily weather variables include maximum and minimum temperature, rainfall, wind speed, cloud cover, and sunshine. Multi-level mixed-effects linear regression models were the primary statistical approach used.

Chapter 6 (original study 4) explores the associations between movement-related behaviours of Australian adults (ARIA) and vacationing away from usual paid or unpaid work. Multi-level mixed-effects linear regression models are used to compared pre-vacation movement behaviours durations to during and post-vacation durations. Additional comparisons using the same analysis approach are reported to examine associations with vacation type and vacation duration.

The thesis concludes with an overall summary and discussion of the main findings (Chapter 7). This includes key contributions to current literature on annual rhythms in movement-related behaviours and recommendations for future research directions.

Declaration

I declare that:

a) this thesis presents work carried out by myself and does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university;
b) to the best of my knowledge, it does not contain any materials previously published or written by another person except where due reference is made in the text; and
c) all substantive contributions by others to the work presented, including jointly authored publications, is clearly acknowledged.



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Publications and presentations

Publications accepted

1. **Ferguson T**, Curtis R, Fraysse F, Lagiseti R, Northcott C, Virgara R, Watson A, Maher C. Annual, seasonal, cultural and vacation patterns in sleep, sedentary behaviour and physical activity: a systematic review and meta-analysis. BMC Public Health. 2021;21(1):1384.
2. **Ferguson T**, Curtis R, Fraysse F, Olds T, Dumuid D, Brown W, Esterman A, Maher C. Weather associations with physical activity, sedentary behaviour and sleep patterns of Australian adults: a longitudinal study with implications for climate change. International Journal of Behavioral Nutrition and Physical Activity. 2023;20(1):30.
3. **Ferguson T**, Curtis R, Fraysse F, Olds T, Dumuid D, Brown W, Esterman A, Maher C. How do 24-hour movement behaviours change during and after vacation? A cohort study. International Journal of Behavioral Nutrition and Physical Activity. 2023;20(1):24.

Publications under review

1. **Ferguson T**, Curtis R, Fraysse F, Olds T, Dumuid D, Brown W, Esterman A, Maher C. The annual rhythms in sleep, sedentary behaviour and physical activity of Australian adults: a prospective cohort study. International Journal of Epidemiology. 2023; m*anuscript under review.*

Conference presentations

1. **Ferguson T**, Curtis R, Fraysse F, Olds T, Dumuid D, Brown W, Esterman A, Maher CA. The associations between weather conditions and adults' 24-hour movement behaviours: a prospective cohort study. International Society for Physical Activity and Health, Abu Dhabi, United Arab Emirates, 23-26 Oct 2022. (in-person presentation)
2. **Ferguson T**, Curtis R, Fraysse F, Olds T, Dumuid D, Brown W, Esterman A, Maher CA. How do 24-hour movement behaviours change during and after vacation? A cohort

study. International Society for Physical Activity and Health, Abu Dhabi, United Arab Emirates, 23-26 Oct 2022. (poster)

Co-authored publications using the ARIA study dataset

1. Curtis RG, Olds T, Fraysse F, Dumuid D, Hendrie GA, Esterman A, Brown WJ, **Ferguson T**, Lagiseti R, Maher CA. Annual rhythms in adults' lifestyle and health (ARIA): protocol for a 12-month longitudinal study examining temporal patterns in weight, activity, diet, and wellbeing in Australian adults. BMC Public Health. 2021;21(1):70.
2. Curtis RG, Olds T, **Ferguson T**, Fraysse F, Dumuid D, Esterman A, Hendrie GA, Brown WJ, Lagiseti R, Maher C. Changes in diet, activity, weight, and wellbeing of parents during COVID-19 lockdown. PloS One. 2020;16(3):e0248008.
3. Maher C, **Ferguson T**, Curtis R, Brown W, Dumuid D, Fraysse F, Hendrie G, Singh B, Olds T. Weekly, seasonal and festive period weight gain in Australian adults: a 365-day cohort study. JAMA Network Open. 2022; m*anuscript under review.*

Chapter 1

The temporal context of daily movement

How people spend their days, including how much they sleep, sit and are active, has fundamental impacts on, and is impacted by, their health and wellbeing. This introductory chapter will provide a background on daily movement behaviours, including how they are measured, their associations with health and wellbeing, and secular trends in movement behaviour patterns. Finally, temporal cycles and events will be introduced in the context of current literature. The chapter will conclude with an outline of my thesis aims and structure.

1.1 Daily movement

In simple terms, a person is either sleeping, sedentary or active at any point throughout the day. These movement-related behaviours are of increasing energy expenditure and can be considered on a time-use continuum (see Figure 1.1).[1] These behaviours are co-dependent, with 1440 minutes wholly distributed amongst the behaviours each day.[2] How people use their time is a mix of demands such as employment, household chores or caring duties, and free choice for preferred activities such as social or leisure pursuits. The day-to-day distribution of time is susceptible to fluctuation as demands on time are difficult to predict and preferences for free time are context specific. The temporal context or the "when" of changing time-use is a primary focus of this thesis along with the exploration of temporal cycles and events that may be associated with movement behaviour change.

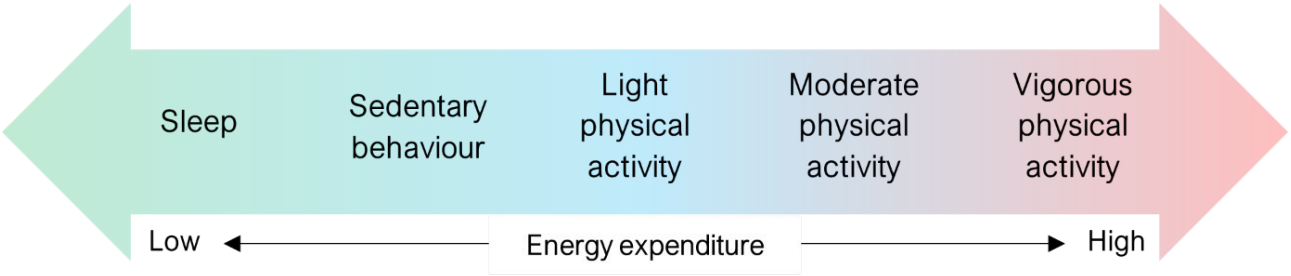


Figure 1.1 - Continuum of movement-related behaviours

1.2 Characteristics of movement-related behaviours

Daily movement is typically categorised using relative energy expenditure; however, sleep, sedentary behaviour and physical activity each have their own distinct characteristics. Firstly, sleep is a brain process characterised by a reversible state of behavioural disconnection and unresponsiveness relative to the environment, typically occurring whilst the body rests.[3] Since the body is at rest, sleep requires the least amount of energy to perform. Similarly, sedentary behaviour is typically defined as a body at rest in either sitting, reclining or lying, however it is also categorised as a waking behaviour where energy expenditure does not exceed 1.5 metabolic equivalents (METs).[4] Physical activity is bodily movement resulting from the contractions of skeletal muscles, characterised by an energy expenditure of greater than a

person's resting metabolic rate.[5] Physical activity is typically separated into intensity-based subcategories of light (e.g. standing, cooking, self-care, <1.5 to <3 METs), moderate (e.g. walking, gentle swimming or cycling, ≥3 to <6 METs) or vigorous physical activity (e.g. running, swimming or cycling where breathing is heavy, ≥6 METs).[6] The differences between each behaviour such as movement vs minimal to no movement and conscious vs unconscious engagement, and the various associated physiological responses, presents a variety of challenges to measuring all movement across a full day.[7]

1.3 Measuring movement-related behaviours

There are various measurement tools available to capture durations of sleep, sedentary behaviour or physical activity. These tools vary widely in validity, reliability, and feasibility.[8-10] Traditionally, measurement tools tended to be unique to each movement behaviour (e.g. polysomnography for measuring sleep; physical activity questionnaires for measuring physical activity; and questionnaire items to measure sedentary behaviour). In the past 10 or so years, increasing attention has been paid to measuring two or more movement behaviours simultaneously.[11] In particular, some tools can capture the full 24-hour day of movement behaviour data. These include direct observation, self-report measures and wearable devices (research-grade accelerometers and consumer wearable devices).

1.3.1 Direct observation

Direct observation is where a study participant is watched and movements are classified according to predefined criteria.[12] It has the potential to be a highly valid and reliable method for measuring the 24-hour movement behaviours of physical activity, sedentary behaviour and sleep, as a trained researcher is able to observe and categorise behaviours in real-time and distinguish non-ambulatory body postures.[12] However, for 24-hour measurement in free-living conditions this is the least feasible single-tool option due to its high burden on participants, intrusion of privacy, susceptibility to reactivity of behaviour, and a large time and cost burden to researchers.[13] Direct observation is commonly used as a criterion for validating other measurement tools over short durations. A commonly used alternative in free-living conditions is self-report.

1.3.2 Self-report

Self-report measures include questionnaires, interviews, and diaries. These methods rely on recall or frequent recording of behaviours over varying durations.[12] There are several advantages to self-report, including being generally low cost, low burden to both researchers and participants, and as such, offering scalability.[14] Accordingly, this method of measurement is widely used in population-level surveillance of movement behaviours.[15, 16] Since questionnaires and interviews rely on the participant remembering their movement patterns, there is a risk of recall bias. In particular, there is an inverse relationship between length and clarity of recall, i.e. the longer into the past the participant is asked to recall, the less detail can be reported.[8] Diaries reduce this issue as data on behaviour is regularly recorded at the time or shortly after the behaviour occurs. Whilst this allows for higher clarity data over longer durations, it is of high burden to participants, and at risk of social desirability bias and reactivity to frequent measurement.[8] These forms of bias are also true of questionnaires and interviews.[8, 12] Advances in wearable technology have seen accelerometry-based devices become a viable alternative to self-report measures.

1.3.3 Research-grade accelerometers

Over the past few decades, accelerometers have become increasingly used in movement behaviour research (see Figure 1.2). Research-grade accelerometers are typically tri-axial, capture three-dimensional accelerations, and are commonly worn on the hip, wrist or more recently the thigh.[17] These devices are commonly used as measurement tools and have been shown to have medium-to-high validity and reliability for measuring sleep, sedentary behaviour and physical activity.[7, 12, 18] Accelerometry offers several advantages over self-report tools. Specifically, there is no reliance of participant recall, they are relatively small and low-to-moderate burden for participants, offer continuous measurement over extended periods (days to weeks) and typically lack immediate feedback via displays.[8] Some disadvantages do exist, however. These include being historically costly (but this is improving over time), limited on-board memory and battery life which restricts data collection windows, and requiring specific skills to process and interpret the raw accelerometry data.[19] Additionally, there is variable accuracy with non-ambulatory activities (i.e. cycling, swimming) and user adherence to wearing the devices is a challenge with longer measurement periods.[20] In the last decade the technology underpinning research-focused devices have become available to the average consumer via wearable activity trackers.

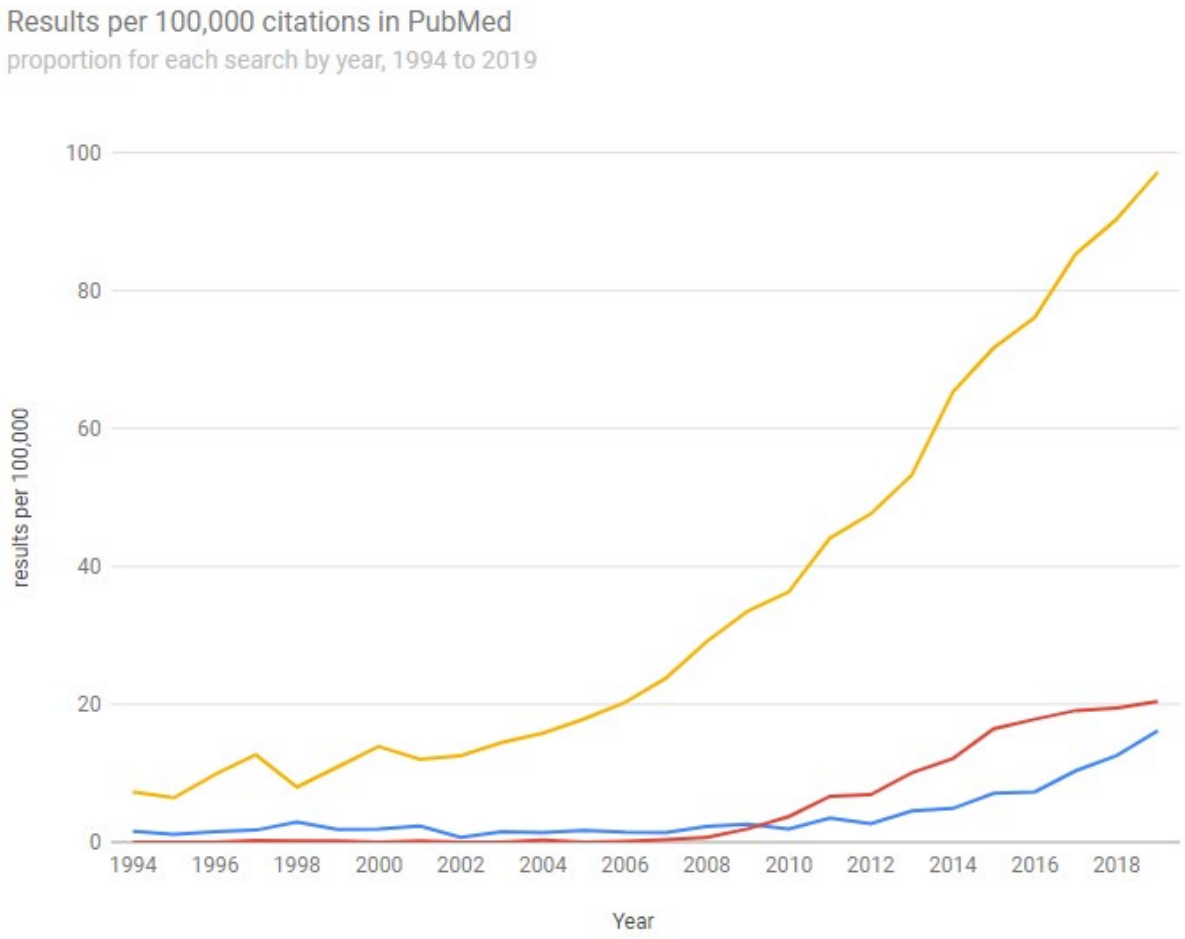


Figure 1.2 - PubMed results per 100,00 citations for wearables and movement behaviours

Notes: blue = sleep, red = sedentary behaviour, yellow = physical activity. Search terms used = accelerometer OR activity tracker OR fitness tracker OR activity monitor OR fitness monitor OR wearable AND adult AND [one of sleep, sedentary behaviour, or physical activity]

1.3.4 Consumer wearable devices

The global consumer wearables market has boomed over the past decade with an estimated USD $2.8 billion spent on wearables in 2020 alone.[21] Consumer wearables such as activity trackers and smart watches, tend to be multi-sensor, generally accompanying an accelerometer with additional sensors such as a heart rate monitor, inclinometer, altimeter, global-positioning system, gyroscope or temperature sensor to gain richer data than accelerometer-only devices.[22] Importantly, using multiple sensors allows for more accurate capture of non-ambulatory activity and non-active behaviours (sleep and sedentary behaviour) allowing for greater accuracy in capturing 24-hour movement.[20] A large body of evidence is emerging regarding the reliability and validity of wearable activity trackers.[23-26] With the rapid expansion of the wearable market, it is a challenge for validation studies of these

devices to keep pace with new models. However, taken together, there is considerable evidence that these devices, particularly the more established brands such as Fitbit, Garmin and Apple, have acceptable validity and reliability for sleep, sedentary behaviour and physical activity duration and are comparable with research-grade accelerometers.[20, 27] Consumer wearable devices provide several benefits as research tools: they have comparable accuracy to research-grade devices whilst being lower-cost options, they are generally user-friendly, contain multiple sensors and measure a variety of outcomes.[22] Some limitations of consumer wearables in research settings include reactivity to real-time feedback and algorithms for categorising behaviours are largely not shared by manufacturers.[28] Irrespective of the tool used, measuring movement behaviours allows for exploration of how movement is associated with health and wellbeing outcomes.

1.4 Associations with health and wellbeing

Sleep, sedentary behaviour and physical activity are all associated with a person's health and wellbeing.[11] The links between each behaviour and health outcomes are considered in the following sections.

1.4.1 Sleep

Sleep typically has a U-shaped relationship with health outcomes, with the optimal sleep duration for adults appearing to be between 7 to 8 hours per day for the most favourable outcomes.[29] A 2020 overview of systematic reviews by Chaput et al. reported on 11 reviews with over 4 million participants, exploring 14 health outcomes, including mortality, incidence of cardiovascular disease, type 2 diabetes, mental health, and obesity, cognitive functions, falls, accidents and injuries, and osteoporosis risk.[29] The overview found a collective U-shaped association between sleep and the included outcomes, with short and long sleep durations being associated with poorer health.[29] In addition to long term associations with sleep, there are acute effects associated with sleep loss. Sleep loss (multiple days of sleep restricted to 50-75% of usual or an 8 hour duration) and single short sleep durations (<6 hours per day) are associated with numerous deficiencies, such as reduced exercise performance (e.g. skill, strength, speed, endurance and power),[30] reduced accuracy and delayed reaction time for

cognitive task such as simple and complex attention, processing, working and short term memory and reasoning,[31] impaired decision making,[32] and increased levels of inflammation.[33]

1.4.2 Sedentary behaviour

Sedentary behaviour typically has an inverse relationship with favourable physical and mental health outcomes, where higher sedentary time is linked with poorer outcomes.[34] For example, longer durations of sedentary behaviour are associated with reduced physical and cognitive function, increased risk of depression and disability, and reduced health-related quality of life.[34] Additionally, longer durations of sedentary behaviour increase the risk of developing type 2 diabetes or cardiovascular disease, and increased risk of cardiovascular-related mortality and all-cause mortality.[35] The opposite relationship appears to exist for physical activity.

1.4.3 Physical activity

Broadly, physical activity has been shown to have a favourable association with risk of non-communicable diseases, body composition, physiological and mental health outcomes and mortality risk.[36] Much of the literature has focused on overall physical activity, meeting national guidelines or higher intensities, i.e. moderate-to-vigorous intensity physical activity.[36-41] In recent years, increasing attention has been paid to the health associations with light physical activity, generally suggesting that similar benefits, though lesser in magnitude, are conferred. This includes favourably associations with obesity, waist-circumference, trigycleride levels, insulin, the presence of metabolic syndrome, and all-cause mortality risk.[42, 43] The opposing associations of physical activity and sedentary behaviour supports the notion that daily movement behaviours are interlinked.

1.4.4 Interactions between behaviours

Relationships between behaviours is partially a product of their co-dependency in terms of daily time allocation, but also due to a variety of reciprocal relationships between behaviours linked via physiological pathways.[44] For example, more physical activity is linked to more sleep through decreased insulin resistance and inflammation markers, improved circadian rhythm regulation and release of brain-derived neurotropic factor.[44] The other side of this relationship is sleep deprivation, which may alter physical performance and increase onset of fatigue during physical activity through increased cortisol and inflammation and decreased growth hormone and prolactin.[45] Additionally, the amount and daily mix of movement behaviours is

likely to have varied associations with favourable health outcomes (e.g. more physical activity may have a different association with physical health outcomes depending on whether time is taken from sleep or sedentary behaviour each day).[46] Public health recommendations attempt to summarise these relationships to provide clear guidance for the public and policy makers.[11]

1.5 Public health movement guidelines

Public health guidelines provide recommendations and targets for movement patterns to optimise health and have been available in many countries for decades.[14] Australia first published physical activity guidelines in 1999, recommending adults achieve 30 minutes of moderate-to-vigorous physical activity on most days of the week.[47] The addition of sedentary behaviour to the Australian guidelines is a more recent occurrence, first appearing in the 2014 update.[48] Currently, Australian physical activity and sedentary behaviour guidelines reflect global guidelines published by the World Health Organisation (WHO). These include a weekly accumulation between 150 to 300 minutes of moderate physical activity or 75 to 150 minutes of vigorous physical activity, or a combination of both, and limiting sedentary time and replacing it with physical activity.[48] Australia and the WHO do not publish sleep recommendations, and these are surprisingly uncommon for adults in most countries. The US National Sleep Foundation is commonly cited as a source of recommended sleep duration for adults, suggesting 7 to 9 hours of sleep per day for optimal health outcomes.[49] In recent years, there has been a shift towards considering movement across the whole day with new 24-hour movement guidelines emerging.

Increased focus on whole day movement is in response to the emerging knowledge base on the impacts of whole-day movement on health outcomes and the influence these behaviours have on one another.[11, 50] Several 24-hour guidelines have been published in recent years, mostly focused on children and young adults.[51-55] At present, only two countries have 24-hour movement guidelines for adults: Thailand and Canada.[56, 57] Thailand introduced their guidelines in 2017, providing duration targets for sleep and physical activity, and limiting sedentary behaviour bouts to 2 hours or less.[57] The Canadian guidelines are the closest to providing duration targets for all movement-related behaviour, with light physical activity being the only behaviour with a non-specific target of “several hours” per day.[56] National and

international movement guidelines play an important supporting role by providing targets for healthy movement and giving context to secular trends at the population-level.

1.6 Secular trends, prevalence and economic burden of movement behaviours

Secular trends suggest many countries have seen a shift from physically active to more sedentary lifestyles over recent decades.[58] Additionally, there has been a shift in the type of physical activity, with more leisure time physical activity and less occupational physical activity.[59] Since the advent of physical activity guidelines several decades ago, global trends on meeting physical activity guidelines appear relatively stable.[16] Evidence suggests that adults' sleep duration has generally remained stable over recent decades, despite widely held perceptions that sleep is declining.[60-62] Worldwide estimates of the prevalence of unfavourable patterns of physical activity, sedentary behaviour and sleep are of concern.

Globally, it is estimated 27.5% of the population is insufficiently active.[63] This has led to an estimated global economic burden in 2013 of INT $67.5 billion in health care expenditure and lost productivity.[64] In Australia, just under half (45.4%) of adults were sufficiently active in 2017-2018, almost double the global estimate.[65] Australian adults were generally less active the older they were (71.9% of 65+ year olds vs. 50.5% of 18-64 year olds were insufficiently active) and the lower their socioeconomic status (37% low SES vs. 52% high SES).[65] Similarly, global estimates of sleep durations suggest up to 10% of people are sleeping less than 6 h/day and approximately a third are sleeping longer than 9 h/day (range = 23-41%).[66] The financial loss attributed to insufficient sleep (<7 h/day) has been estimated at between 1-3% of total yearly economic revenue across five large economies (US, UK, Japan, Germany and Canada), the equivalent of up to USD $680 billion.[67] In Australia, more than $2 billion is spent on preventive health each year; a key focus of this expenditure is health promotion.[68]

Health promotion campaigns typically intervene based on geography (e.g. rural and remote regions), demography (e.g. targeted ethnic groups) or socioeconomics (e.g. low socioeconomic status groups). A key factor that may be overlooked is the timing of health promotion delivery. Whilst secular trends are broadly understood, intra-annual temporal

factors such as season, cultural and festive periods, and vacations may be influential disruptors of movement behaviour patterns, however research on these remain scarce.

1.7 Temporal patterns

Temporal factors that may disrupt movement behaviour patterns can be either cyclical or periodic events. Temporal cycles are those that follow a defined pattern over time and repeat across a set time period, e.g. days of the week, and months or seasons in a year. [69] Whereas temporal events are those that occur when a specific point in time is reached, and have a beginning and an end, e.g. daylight saving time transitions, national, cultural or religious festivals and holidays or vacations.[70] Whilst global surveillance of secular trends in movement behaviours is well established (i.e. changes over several decades), within-year changes in 24-hour movement is largely unexplored to date.[71]

On a daily basis, we experience many small events that prompt specific behavioural responses, i.e. waking up may be linked with self-care activities, beginning of a work day may require commuting to the work place, meal time requires gathering and/or consuming of food.[72] When considering movement-related behaviours, the culmination of the behavioural responses to these person-specific events influences the distribution of time-use across all behaviours each day. Person-specific events are susceptible to daily change, particularly when considering external events outside a person's control (e.g. transport delays whilst commuting, unexpected illness). There is evidence to suggest life-change events such as changes in relationships, family structure, residence, employment status or physical status affect physical activity patterns and engagement, however these are specific to the individual's circumstances.[73] Temporal cycles and events experienced by broader society may have far-reaching effects on population-level movement patterns and in turn health outcomes. Movement behaviour interventions to date have tended to overlook the temporal context of movement patterns.

Interventions aimed at improving movement behaviour patterns have generally focused on sociodemographic factors, including specific life stages, sex or socioeconomic status, and

geographic locations (e.g. regional). However, it is likely there are temporal factors that are associated with unfavourable changes in movement patterns.

1.8 Thesis aims

The overarching aim of this thesis is to explore temporal patterns in daily movement-related behaviour (sleep, sedentary behaviour and physical activity) of adults over a year-long timescale. Further, the thesis seeks to understand how daily movement behaviours vary across the year, according to the weather, work demands, and season. This may identify new intervention targets to address the growing problem of chronic disease. Further, identifying when and how patterns change will highlight potentially unfavourable timepoints for movement patterns (i.e. insufficient or excess sleep, increased sedentary behaviour or decreased physical activity) and provide a temporal framework for optimising the timing of movement-focused interventions or health promotion.

1.9 Thesis structure

This thesis explores the annual temporal patterns of daily movement-related behaviours in adults. The body of the thesis comprises five chapters, with Chapters 2, 4, 5, and 6 presented in manuscript form (and formatted to match the style of the overall thesis:

- Chapter 2 is a comprehensive systematic review and meta-analysis exploring the current literature on intra-annual patterns of daily movement behaviours in healthy adults and the temporal factors that appear to influence these.

- Chapter 3 describes the methods of the Annual Rhythms In Adults' lifestyle and health (ARIA) study, a recently completed National Health and Medical Research Council (NHMRC) funded study. It also outlines my major contribution to the conduct of the study.

- Chapter 4 is the main movement behaviour study arising from the highly novel ARIA dataset. It explores the 24-hour movement behaviour patterns of Australian adults across a full year and analyse the associations between temporal cycles (e.g. day of the week and seasons) and events (i.e. Christmas – New Years, and daylight saving transitions) and fluctuations in movement behaviour patterns.

- Chapter 5 explores the associations between weather conditions (maximum temperature, minimum temperature, rainfall, wind speed, cloud cover and sunshine) and daily movement behaviours in Australian adults.

- Chapter 6 describes the characteristics of vacations taken by participants during the ARIA study, examines the changes in daily movement behaviours from before vacation, to during, and post-vacation periods, and how these changes vary depending on the type of vacation and vacation duration.

The thesis concludes with a discussion chapter which summarises the key findings and contributions of the literature contained in the previous chapters, along with recommendations for future research directions.

Chapter 2

Annual, seasonal, cultural and vacation patterns in sleep, sedentary behaviour and physical activity: a systematic review and meta-analysis

This chapter presents the manuscript of a published systematic review and meta-analysis. The primary aim of the systematic review and meta-analysis is to explore the existing literature on intra-annual temporal factors associated with changes in daily movement behaviour patterns. The manuscript has been formatted to match the style of the overall thesis. The original article is included as Appendix 2.1.[71] A signed Statement of Authorship form for the relative contribution of all authors to this manuscript is included in Appendix 2.2.

Citation:
Ferguson T, Curtis R, Fraysse F, Lagiseti R, Northcott C, Virgara R, Watson A, Maher C. Annual, seasonal, cultural and vacation patterns in sleep, sedentary behaviour and physical activity: a systematic review and meta-analysis. BMC Public Health. 2021;21(1):1384.

2.1 Abstract

Background

Time spent in daily activities (sleep, sedentary behaviour and physical activity) has important consequences for health and wellbeing. The amount of time spent varies from day to day, yet little is known about the temporal nature of daily activity patterns in adults. The aim of this review is to identify the annual rhythms of daily activity behaviours in healthy adults and explore what temporal factors appear to influence these rhythms.

Methods

Six online databases were searched for cohort studies exploring within-year temporal patterns (e.g. season effects, vacation, cultural festivals) in sleep, sedentary behaviour or physical activity in healthy 18 to 65 year old adults. Screening, data extraction, and risk of bias scoring were performed in duplicate. Extracted data was presented as mean daily minutes of each activity type, with transformations performed as needed. Where possible, meta-analyses were performed using random effect models to calculate standardised mean differences (SMD).

Results

Of the 7009 articles identified, 17 studies were included. Studies were published between 2003 and 2019, representing 14 countries and 1951 participants, addressing variation in daily activities across season (n = 11), Ramadan (n = 4), vacation (n = 1) and daylight saving time transitions (n = 1). Meta-analyses suggested evidence of seasonal variation in activity patterns, with sleep highest in autumn (+12 minutes); sedentary behaviour highest in winter (+19 minutes); light physical activity highest in summer (+19 minutes); and moderate-to-vigorous physical activity highest in summer (+2 minutes) when compared to the yearly mean. These trends were significant for light physical activity in winter (SMD = -0.03, 95% CI -0.58 to -0.01, P = 0.04). Sleep appeared 64 minutes less during compared to outside Ramadan (non-significant). Narrative analyses for the impact of vacation and daylight saving time transitions suggested that light physical activity is higher during vacation and that sleep increases after the spring daylight saving time transition, and decreases after the autumn transition.

Conclusions

Research into temporal patterns in activity behaviours is scarce. Existing evidence suggests that seasonal changes and periodic changes to usual routine, such as observing religious events, may influence activity behaviours across the year. Further research measuring 24-hour time use and exploring a wider variety of temporal factors is needed.

Keywords

Sleep, sedentary behaviour, physical activity, systematic review, temporal patterns, seasonal, vacation, cultural patterns, adults, time-use.

2.2 Background

Insufficient sleep, excessive sedentary behaviour and insufficient physical activity are all common drivers of weight gain and obesity in adults.[74, 75] These suboptimal daily movement behaviours also increase the risk of many non-communicable diseases (i.e. coronary heart disease, high blood pressure, type 2 diabetes), all-cause mortality, certain cancers, anxiety, and depression.[34, 42, 76-80] Globally, it is estimated 27.5% of people are insufficiently active,[81] and a third (32%) report high levels of sedentary behaviour (>7 hours a day)[82], resulting in a global economic burden in 2013 of INT $67.5 billion in health care expenditure and lost productivity.[83] A 2017 multi-country study found the percentage of people reporting insufficient sleep (< 7 hours per night)[84] ranged from 26% (Canada) to 56% (Japan).[85]

Substantial resources are put into preventive health each year, including communicable disease control and health promotion (fostering healthy lifestyles, i.e. physical activity).[68] Current health promotion campaigns typically intervene based on geography, demography (e.g. age or ethnicity) or socioeconomics (e.g. disadvantaged groups),[86-88] yet the timing of health promotion campaign delivery may be overlooked. Temporal factors such as season, cultural and festive periods, and vacation status may influence 24-hour movement behaviours. Better understanding temporal patterns in adult movement behaviours may identify new health promotion campaign intervention targets.

Research exploring the temporal factors affecting movement behaviours is scarce. One previous systematic review (n = 37 studies) suggested that physical activity varied with season, being lower in winter and higher in summer.[89] However, this study was limited to physical activity only, and involved only narrative synthesis. No other reviews appear to explore temporal factors in movement behaviours. Consistent with contemporary approaches to viewing physical activity along with sedentary behaviour and sleep as forming the 24h day, this review will consider the impact of temporal factors on all movement behaviours , and use a meta-analytic synthesis, to address the research question: What are the annual rhythms of daily movement behaviours (sleep, sedentary behaviour, light physical activity, and moderate-to-vigorous physical activity) in healthy adults, and what temporal factors appear to influence these?

2.3 Methods

2.3.1 Protocol and registration

This review follows PRISMA guidelines[90] and was registered on PROSPERO (ID CRD42020184012).[91]

2.3.2 Eligibility criteria

Studies were included if: they were cohort studies reporting objectively or subjectively measured minutes of sleep, sedentary behaviour, and/or physical activity (light and moderate-to-vigorous); participants were healthy adults aged 18 to 65 years (reflecting the typical age range of adults in health behaviour guidelines); the study explored a temporal pattern (e.g. seasonal effects, pre/post/during vacation or cultural festivals); and the study included at least two assessment time points within a 12-month period using a within-subject design (the most robust design for addressing our research question). Intervention and cross-sectional study designs were excluded along with studies exploring non-general population samples and studies conducted in controlled settings. Studies comparing weekdays to weekends were excluded if only one time point was measured, however longitudinal studies using this comparison were included and weekly means calculated. Studies with populations that spread outside the eligible age range were included if data were able to be extracted (or obtained from authors) for only those participants aged 18 to 65 years.

2.3.3 Information sources and search strategy

The search strategy was developed in consultation with an academic librarian. Six databases were searched in 2020; Embase, Medline, Ovid Emcare, Scopus, Sport Discus, and Web of Science. Temporal patterns included terms relating to seasons, holidays, vacations, and festivals. Specific terms relating to religious events were included for the three most commonly observed religions: Christianity, Islam and Hinduism.[92] Where possible, searches were limited to English language, humans, and adults 18-65 years of age. Athlete* or player* were excluded terms and no limitation was placed on date range. Figure 2.1 shows the search strategy used for Medline.

Line	Search term	Result
1	Adult/	4910909
2	adult*.ti,ab,kw.	1211711
3	Exercise/	105807
4	(physical activit* or exercis*).ti,ab,kw.	372960
5	Sedentary Behavior/	8777
6	sedentary behavio?r*.ti,ab,kw.	6350
7	Sleep/	51468
8	sleep*.ti,ab,kw.	177205
9	Seasons/	104262
10	Holidays/	2853
11	(temporal pattern* or time pattern* or season* or holiday* or vacation* or festival*).ti,ab,kw.	169537
12	(Christmas or Thanksgiving or Easter or Ramadan or Diwali or Deepawali).ti,ab,kw.	3969
13	1 or 2	5647011
14	3 or 4 or 5 or 6 or 7 or 8	569167
15	9 or 10 or 11 or 12	220809
16	13 and 14 and 15	2500
17	limit 16 to (english language and humans)	2195
18	limit 17 to ("young adult (19 to 24 years)" or "adult (19 to 44 years)" or "middle age (45 to 64 years)")	2042
19	(athlete* or player*).ti,ab,kw.	99086
20	18 not 19	1618

Figure 2.1 - Medline database search terms

2.3.4 Study selection

All studies were imported into EndNote (EndNote x9, Clarivate, Philadelphia, USA) for duplicate removal. Remaining studies were exported to Covidence (Covidence systematic review software, Veritas Health Innovation, Melbourne, Australia) for screening. Two independent reviewers completed title and abstract and full-text screening, with a third reviewer consulted for disagreements.

Where necessary, authors of potentially eligible studies were emailed to request additional data. Reference lists of included studies were searched to identify additional studies.

2.3.5 Data collection

Two independent reviewers used a custom data extraction template, including: study design, exposure (e.g. season, vacation, cultural festival), participant characteristics (sample size, setting, age, sex), outcomes measured (sleep, sedentary behaviour and physical activity), tool

used (e.g. accelerometry, questionnaire), assessment time points (duration and frequency), and results (means and standard deviations for daily minutes of each outcome).

2.3.6 Risk of bias in individual studies

Each study was appraised by two independent reviewers using the Joanna Briggs Institute (JBI) critical appraisal checklist for cohort studies.[93] Conflicts were resolved by a third reviewer. Three items (1, 2 and 6) were irrelevant to single-group study designs and were removed. Each item was rated "yes", "no", "unclear", or "not applicable". Studies were not excluded based on risk of bias results.

2.3.7 Data analysis

The primary outcome measure was mean daily minutes spent in sleep, sedentary behaviour, light physical activity and moderate-to-vigorous physical activity. Where moderate and vigorous physical activity were presented separately, the values were added. Where required, data was converted to be expressed as mean daily minutes. This involved combining groups where appropriate (e.g. combining males and females where reported separately), converting monthly data to seasonal data, and converting weekly data to daily data. Standard errors were converted to standard deviations. Where more than 10 studies are identified for an outcome, funnel plots will be used to examine publication bias.[94]

Meta-analysis was conducted for outcome and exposures reported in multiple studies. For studies presenting seasonal data, an overall yearly mean (minutes per day) for each outcome was calculated to allow for comparisons with seasonal means. For studies exploring Ramadan, during-Ramadan data were compared with pre/post-Ramadan data. Where multiple data points were reported during or pre/post Ramadan, overall means were calculated by combining relevant data for each condition. A random-effects model was used to calculate standardised mean difference (SMD), pooled SMD, and associated confidence intervals (CI), along with forest plots generated using Review Manager (version 5.4, The Cochrane Collaboration). For seasonal data, estimates of the weighted mean difference (WMD) were calculated as the season mean minus the yearly mean expressed as minutes per day. Each calculation was performed by multiplying the overall yearly standard deviation by the SMD for the season of interest. Estimates of the WMD for during Ramadan compared with outside Ramadan was calculated by multiplying the overall standard deviation for outside-

Ramadan by the SMD for during-Ramadan and expressed as minutes per day. Heterogeneity was assessed using the i^2 statistics, calculated using Review Manager. Instead, data are analysed narratively. Analyses were performed in 2020.

2.4 Results

2.4.1 Included studies

The search identified 7009 results, including 4038 different studies, of which 3967 were deemed ineligible based on titles and abstracts. Of the 71 studies reviewed in full text, a further 54 studies were ineligible for several reasons, including 25 had an ineligible study design (e.g. experimental study or cross-sectional), 21 did not report an outcome of interest (minutes of activity), seven had an ineligible population (e.g. children, over 65 yrs, disease populations) and one full-text version of the study was unavailable after extensive searching. 17 studies, published between 2003 and 2019, were included (see Figure 2.2). Two of the included studies became eligible as a result of contact with authors who provided additional data of interest.[95, 96]

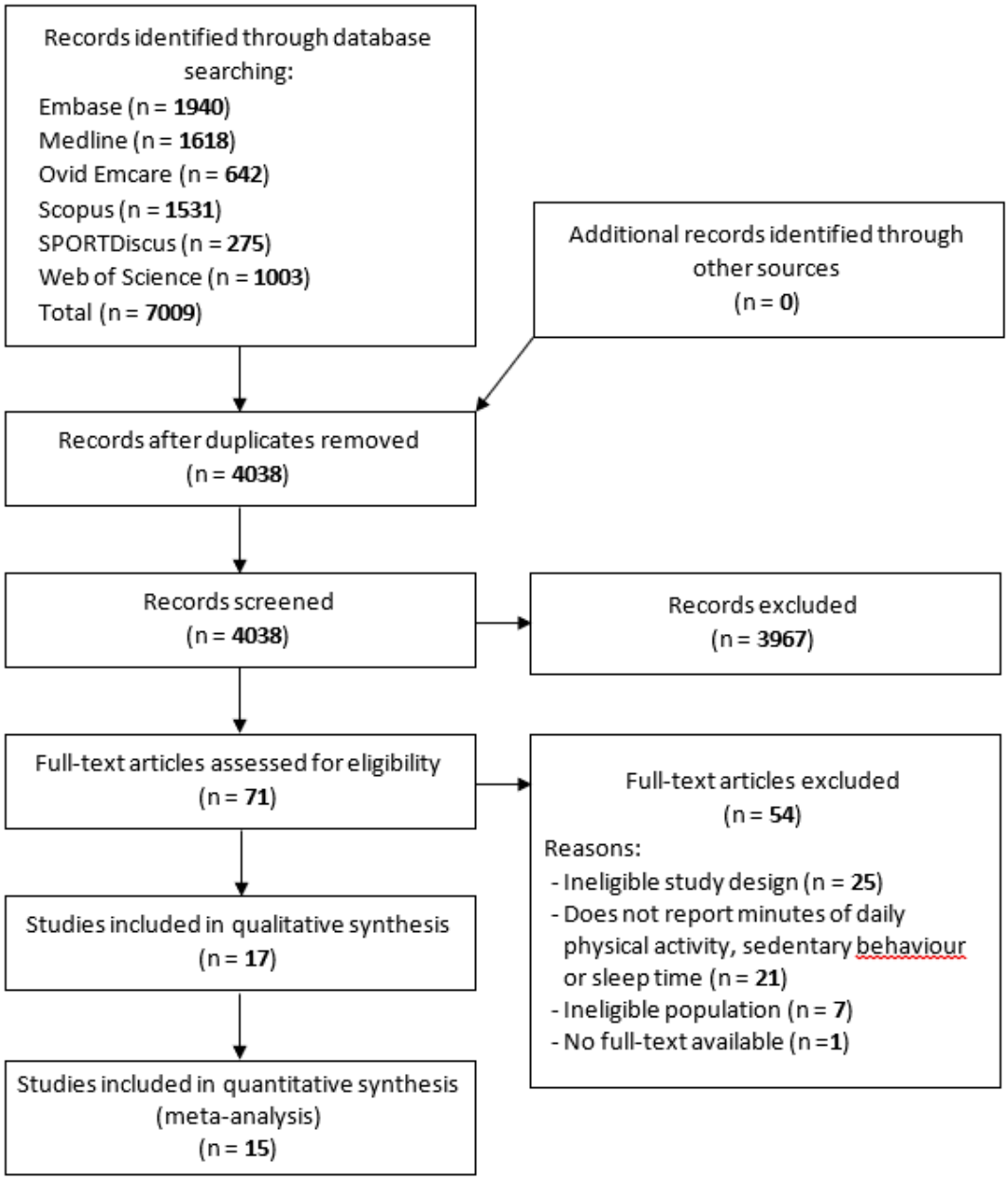


Figure 2.2 - PRISMA flow-chart

2.4.2 Study characteristics

Table 2.1 presents a summary of the included studies. Of the 17 included studies, four temporal exposures were present: seasonal patterns (n = 11),[96-106] Ramadan (n = 4)[107-110] vacation (n = 1),[95] and daylight saving time transitions (n = 1).[111] Studies were conducted across four continents: Europe, Africa, Asia, and North America. Most recruited participants from a single country, however, three studies included two or more countries.[96, 99, 100] Multiple studies were conducted in the USA (n = 4),[95, 98, 102, 103] Saudi Arabia (n = 3),[107, 108, 110] Sweden (n = 2)[97, 100] and England (n = 2),[104, 105] with single studies from Ghana,[99] Norway,[99] Denmark,[100] Germany,[101] Czech Republic,[96] Slovakia,[96] Poland,[96] Japan,[106] Italy,[111] and Libya.[109]

Table 2.1 - Summary of included studies (N=17)

Study	Temporal pattern	Population	Age- mean (SD), range, % female	Outcome	Tool	Assessment- length, total, frequency
Tonetti 2013 [111]	Daylight saving time	University students, Italy (n = 14)	26.9 (3.3), 21-30, 0%	Sleep	Accelerometer: Actiwatch AW-64	7 days x2, pre/post DST transition
BaHammam 2003 [107]	Ramadan	Fasting Muslim medical students, Saudi Arabia (n = 56)	22.6 (1.3), range NR, 45%	Sleep	Questionnaire^	5 weekdays x4, pre/during Ramadan
BaHammam 2005 [110]	Ramadan	Healthy adults, Saudi Arabia (SF n = 41 & NSF n = 30)	SF: 32.6 (1.5), range NR, 39%. NSF: 29.3 (1.6), range NR, 44%	Sleep	Questionnaire^	5 weekdays x3, pre/during Ramadan
BaHammam 2013 [108]	Ramadan	Male hospital staff, Saudi Arabia (n = 8)	36.3 (4.5), range NR, 0%	Sleep	Accelerometer: SenseWear Pro Armband	5 weekdays x3, pre/during Ramadan
Waterhouse 2009 [109]	Ramadan	Healthy adults, Libya (n = 20)	Mean NR, range NR, 0%	Sleep	Questionnaire^	1-night x4, pre/during/post Ramadan
Buchowski 2009 [98]	Season (Wi, Su)	Healthy females, USA (n = 57)	36.5 (9.2), 20-54, 100%	SB, LPA, MVPA	Accelerometer: Tritrac-R3D	7 days x3, consecutive seasons
Pechova 2019 [96]	Season (Sp, Au)	Healthy adults, Czech Republic, Slovakia & Poland (n = 50)	61.2 (2.4), 55-65, % NR	SB, LPA, MPA, VPA,	Accelerometer: ActiGraph GT1M	8 days x2, 6-month follow-up

Lloyd 2013 [103]	Season (Wi, Sp, Su, Au)	Mexican American females, USA (n = 36)	33.9 (9.5), 20-63, 100%	MPA, VPA	Questionnaire: National Health and Nutrition Examination Survey	Prior 3 months x5, quarterly
O'Connell 2014 [104]	Season (Wi, Sp, Su, Au)	Healthy adults, England (n = 46)	F: 42.7 (14.8), range NR. M: 39.5 (14.4), range NR, 72%	SB, LPA, MVPA, sleep	Sleep diary^, accelerometer: ActiGraph GT1M	7 days x4, consecutive seasons
Lehnkering 2007 [101]	Season (Sp, Au)	Medical students, Germany (n = 34)	Mean NR, 19-31, 56%	Sleep	Accelerometer: Actiwatch, Sleep diary^	15 days x2, 6-month follow-up
Shochat 2019 [105]	Season (Sp, Au)	University students, England (n = 19)	18.9 (0.8), range NR, % NR	Sleep	Sleep diary: Karolinska Sleep Diary	21 days x2, 6-month follow-up
Adamsson 2018 [97]	Season (Wi, Sp, Su, Au)	Daytime office workers, Sweden (n = 30)	F: 42.6 (10.0), 24-61, M: 45.2 (14.7), 21-64, 67%	Sleep	Sleep diary^	3 weekdays x12, monthly
Garde 2014 [100]	Season (Wi, Sp, Su, Au)	Hospital staff, Sweden (n = 22) & research staff, Denmark (n = 16)	Sweden: 48.8 (9.2), 33-62, 73%. Denmark: 42.1 (9.8), 25-62, 63%	Sleep	Sleep diary: Karolinska Sleep Diary, accelerometer: Actiwatch AW4	1 workday night x12, monthly
Friborg 2012 [99]	Season (Wi, Su)	University students, Ghana (n = 200) & Norway (n = 200)	Ghana- F: 25.4 (7.5), 19-49, M: 25.3 (6.1), 19-51, 48%. Norway- F: 22.7 (4.8), 19-50,	Sleep	Sleep diary^	7 days x2, 6-month follow-up

			M: 22.7 (5.5), 18-54, 73%			
Ludy 2018 [102]	Season (Wi, Su)	University students, USA (n = 60)	18.1 (0.3), range NR, 82%	Sleep	Questionnaire: Youth Risk Behaviour Survey	7 days x2, 4-month follow-up
Suzuki 2019 [106]	Season (Wi, Su, Sp, Au)	Community residents, Japan (n = 960)	YA: mean NR, 19-31, % NR. MA: mean NR, 40-61, % NR	Sleep	Questionnaire^	14 nights x4, consecutive seasons
Cooper 2016 [95]	Vacation	Healthy adults, USA (n = 122)	32.2 (13), range NR, 65%	SB, LPA, MPA, VPA	Questionnaire: International Physical Activity Questionnaire	7 days x3, pre/during/post-vacation

Notes: ^tool purpose designed for study. Au = autumn, F= female, LPA = light physical activity, M= male, MA = middle-aged, MPA = moderate physical activity, MVPA = moderate-to-vigorous physical activity, NR = not reported, NSF= Non-Saudi fasting group, SB = sedentary behaviour, SF= Saudi fasting group, Sp = spring, Su = summer, VPA = vigorous physical activity, Wi = winter, YA = young adult.

2.4.3 Participants

The studies involved a total of 1951 participants, with sample sizes ranging from 8[108] to 960,[106] 14 had sample sizes <n=100. Mean participant age ranged from 18.1 years (SD = 0.3)[102] to 61.2 years (SD = 2.4)[96]. Most studies (n = 12) included mixed sex cohorts (range = 39% to 82% female), two had only female participants,[98, 103] and three had only males.[108, 109, 111]

2.4.4 Primary outcomes

Sleep was the most common activity examined (n = 13),[97, 99-102, 104-111] with sedentary behaviour and light physical activity both measured in four studies,[95, 96, 98, 104] and moderate physical activity and vigorous physical activity measured in five studies, either separately or combined as moderate-to-vigorous physical activity.[95, 96, 98, 103, 104] Ten studies used subjectively measured activity (i.e. survey, questionnaire, sleep diary),[95, 97, 99, 102, 103, 105-107, 109, 110] four studies used objective measures (accelerometry),[96, 98, 108, 111] and three studies used a combination (accelerometer and sleep diary).[100, 101, 104] One study used a 24-hour accelerometry protocol, allowing changes in sleep, sedentary behaviour, light physical activity and moderate-to-vigorous physical activity to be examined simultaneously.[104] Analyses were not performed to detect potential publication bias due insufficient studies for each outcome and subgroup analyses were not performed due to the limited data available.

2.4.5 Critical appraisal

Results from the JBI critical appraisal are presented in Table 2.2. Three studies received 'yes' responses for all items.[96, 98, 104] All studies measured the exposure in a valid and reliable way. Almost half of the studies did not identify confounding factors,[95, 97, 99, 101, 103, 107, 108, 110] nine studies did not state strategies that were used to deal with confounding factors,[95, 97, 99, 101-103, 107, 108, 110] whilst it was unclear for one study if strategies were used.[109] It was unclear whether Suzuki et al.[106] and Waterhouse et al.[109] measured outcomes in a valid and reliable way. More than half of the studies had incomplete follow-up[95, 97, 99, 100, 102, 103, 105-107] whilst completeness of follow-up was unclear for one study.[109] Where follow-up was incomplete or unclear, most reported strategies used to address this, however it was unclear for the studies by Garde et al.[100] and Waterhouse et al.[109]. All studies were deemed to have used appropriate statistical analyses.

Table 2.2 - Joanna Briggs Institute critical appraisal checklist summary table

Question^	Responses																
	Adamsson 2018 [97]	BaHammam 2003 [107]	BaHammam 2005 [110]	BaHammam 2013 [108]	Buchowski 2009 [98]	Cooper 2016 [95]	Friborg 2012 [99]	Garde 2014 [100]	Lehnkering 2007 [101]	Lloyd 2013 [103]	Ludy 2018 [102]	O'Connell 2014 [104]	Pechova 2019 [96]	Shochat 2019 [105]	Suzuki 2019 [106]	Tonetti 2013 [111]	Waterhouse 2009 [109]
3. Was the exposure measured in a valid and reliable way?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
4. Were confounding factors identified?	×	×	×	×	✓	×	×	✓	×	×	✓	✓	✓	✓	✓	✓	✓
5. Were strategies to deal with confounding factors stated?	×	×	×	×	✓	×	×	✓	×	×	×	✓	✓	✓	✓	✓	U
7. Were the outcomes measured in a valid and reliable way?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	U	✓	U
8. Was the follow-up time reported and sufficient to be long enough for outcomes to occur?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×
9. Was follow up complete, and if not, were the reasons to loss to follow up described and explored?	×	×	✓	✓	✓	×	×	×	✓	×	×	✓	✓	×	×	✓	U
10. Were strategies to address incomplete follow up utilized?	✓	✓	✓	✓	✓	✓	✓	U	✓	✓	✓	✓	✓	✓	✓	✓	U
11. Was appropriate statistical analysis used?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Notes: × = no, ✓ = yes, U= unclear. Note – questions 1,2 and 6 omitted as not relevant to included study design.

2.4.6 Temporal factors

Season

Season was the most examined temporal factor, with 11 studies.[96-106]

Sleep (n = 8 studies)

Eight studies reported sleep duration data across seasons (total participants n = 1587).[97, 99-102, 104-106] Figure 2.3 depicts forest plots for sleep in each season compared to the yearly average. Eight studies were included for winter and summer comparisons, and seven for spring and autumn comparisons. No season had significant differences compared to the yearly average. There was a trend towards higher daily minutes of sleep during winter (SMD = 0.05 [95% CI: -0.02 to 0.12], WMD = 4 minutes/day) and autumn (SMD = 0.17 [95% CI: -0.10 to 0.43], WMD = 12 minutes/day), and less during spring (SMD = -0.21 [95% CI: -0.51 to 0.10], WMD = -15 minutes/day) and summer (SMD = -0.06 [95% CI: -0.13 to 0.01], WMD = -4 minutes/day), when compared to the yearly mean. The largest change between seasons was an increase of 27 minutes/day from spring to autumn. Minimal heterogeneity between studies was observed for winter and summer (I^2 = 0%) and substantial heterogeneity was observed for spring and autumn (I^2 = 76% and 69% respectively).

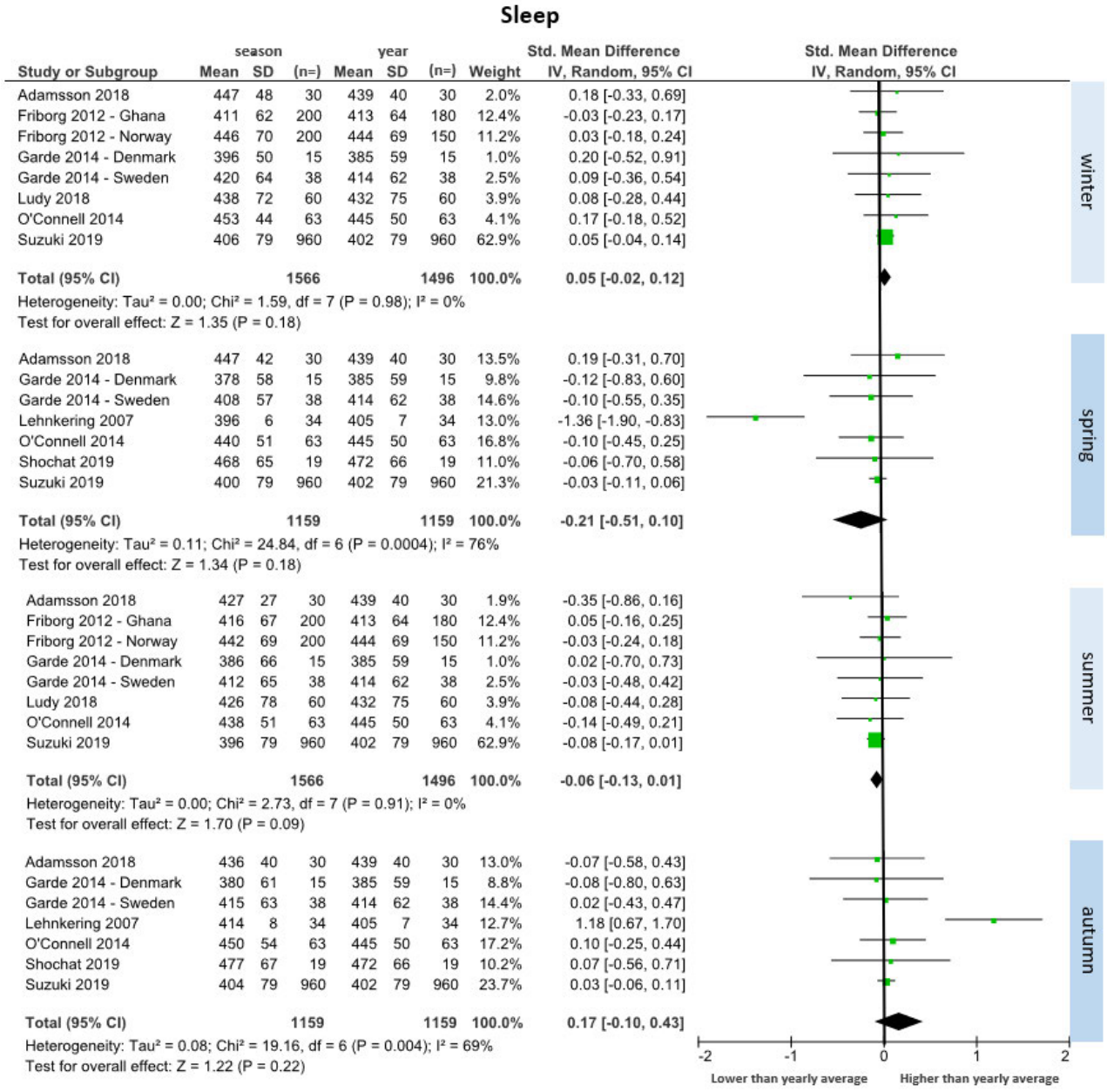


Figure 2.3 - Forest plot of daily minutes of sleep comparing seasonal means with yearly mean

Sedentary behaviour (n = 3 studies)

Three studies reported sedentary behaviour data across seasons (total participants n = 153).[96, 98, 104] Two studies were included in each comparison (Figure 2.4). There were no significant differences in sedentary time in any season compared to the yearly mean. There was a trend towards higher daily minutes of sedentary behaviour during winter (SMD = 0.23 [95% CI: -0.03 to 0.48], WMD = 19 minutes/day) and autumn (SMD = 0.11 [95% CI: -0.15 to 0.37], WMD = 9 minutes/day), and less during spring (SMD = -0.18 [95% CI: -0.44 to 0.08], WMD = -15 minutes/day) and summer (SMD = -0.16 [95% CI: -0.41 to 0.10], WMD = -14 minutes/day), when compared to the yearly mean. The largest change between seasons was

an increase of 36 minutes/day from spring to winter. Minimal heterogeneity between studies was observed across all seasons (I^2 = 0%).

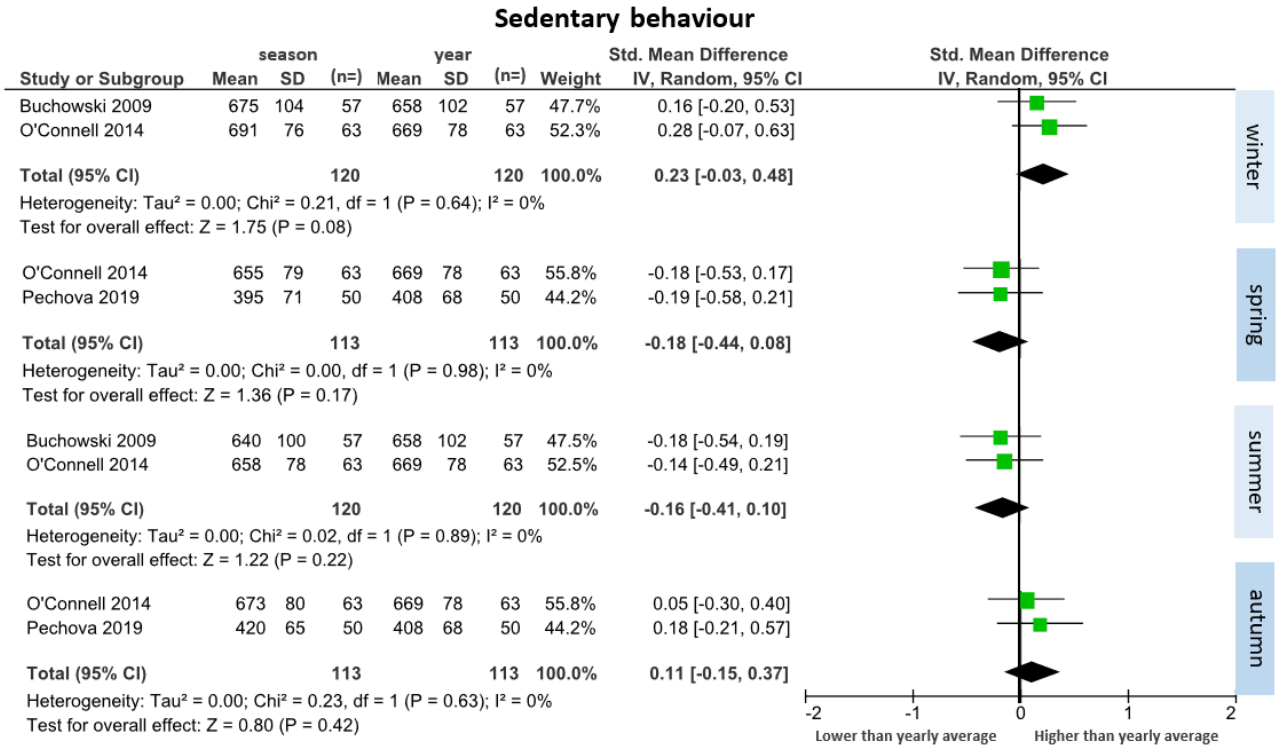


Figure 2.4 - Forest plot of daily minutes of sedentary behaviour comparing seasonal means with yearly mean

Light physical activity (n = 3 studies)

Three studies reported light physical activity data across seasons (total participants n = 153).[96, 98, 104] Two studies were included in each comparison (Figure 2.5). Significantly less light activity occurred during winter compared to the yearly mean (SMD = -0.30 [95% CI: -0.58 to -0.01], WMD = -26 minutes/day). No significant differences were found with the remaining seasons. There was a trend towards more light physical activity during spring (SMD = 0.20 [95% CI: -0.06 to 0.46], WMD = 17 minutes/day) and summer (SMD = 0.22 [95% CI: -0.03 to 0.48], WMD = 19 minutes/day), when compared to the yearly average, and less light physical activity in autumn (SMD = -0.14 [95% CI: -0.40 to 0.12], WMD = -12 minutes/day). The largest change between seasons was an increase of 45 minutes/day from winter to summer. Minimal heterogeneity between studies was observed across all seasons (winter: I^2 = 21%; spring, summer and autumn: I^2 = 0%).

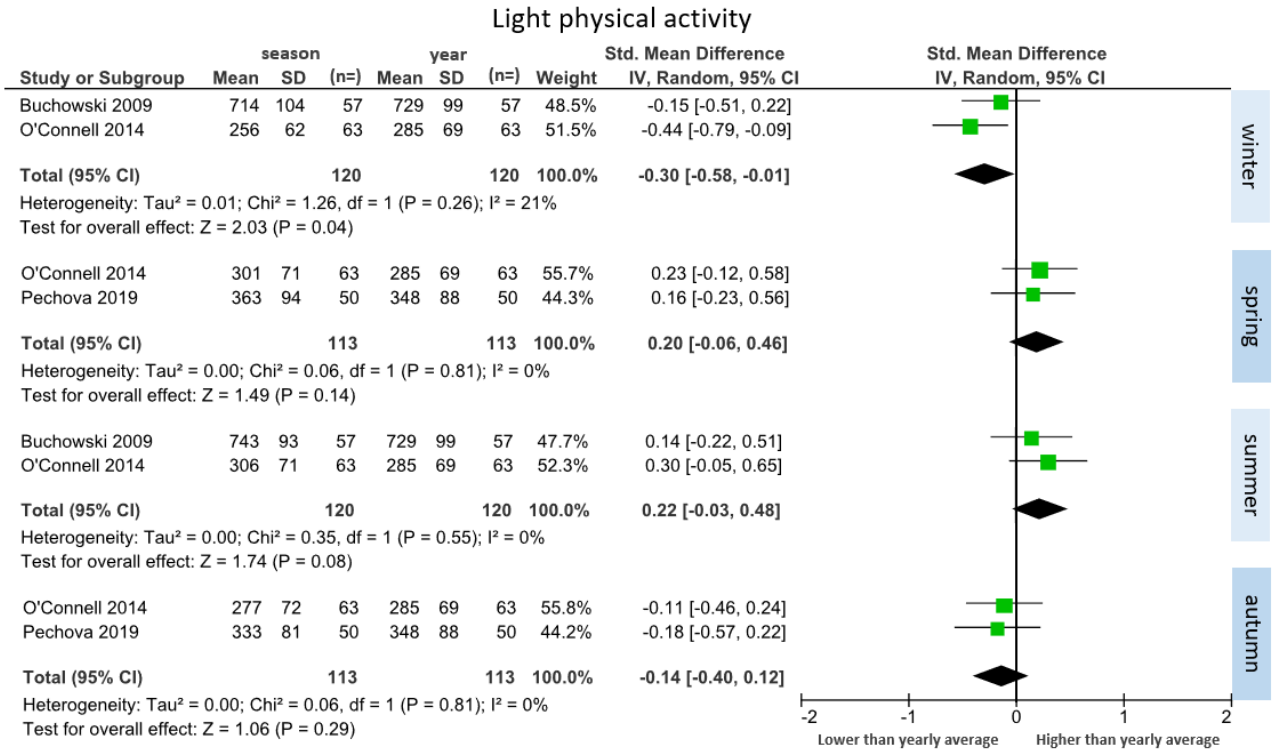


Figure 2.5 - Forest plot of daily minutes of light physical activity comparing seasonal means with yearly mean

Moderate-to-vigorous physical activity (n = 4 studies)

Four studies reported moderate-to-vigorous physical activity data across seasons (total participants n = 189).[96, 98, 103, 104] Three studies were included in each comparison (Figure 2.6). There were no significant differences in any season compared to the yearly average. There was a trend toward less moderate-to-vigorous physical activity during winter (SMD = -0.12 [95% CI: -0.34 to 0.11], WMD = -3 minutes/day) and autumn (SMD = -0.06 [95% CI: -0.28 to 0.17], WMD = -1 minute per day). There was trend toward more moderate-to-vigorous physical activity during summer (SMD = 0.08 [95% CI: -0.14 to 0.31], WMD = 2 minutes/day) and minimal difference from the yearly average for spring (SMD = 0.02[95% CI: -0.20 to 0.25], WMD = 0.5 minutes/day). The largest change between seasons was an increase of 5 minutes/day from winter to summer. Minimal heterogeneity between studies was observed across all seasons (I^2 = 0%).

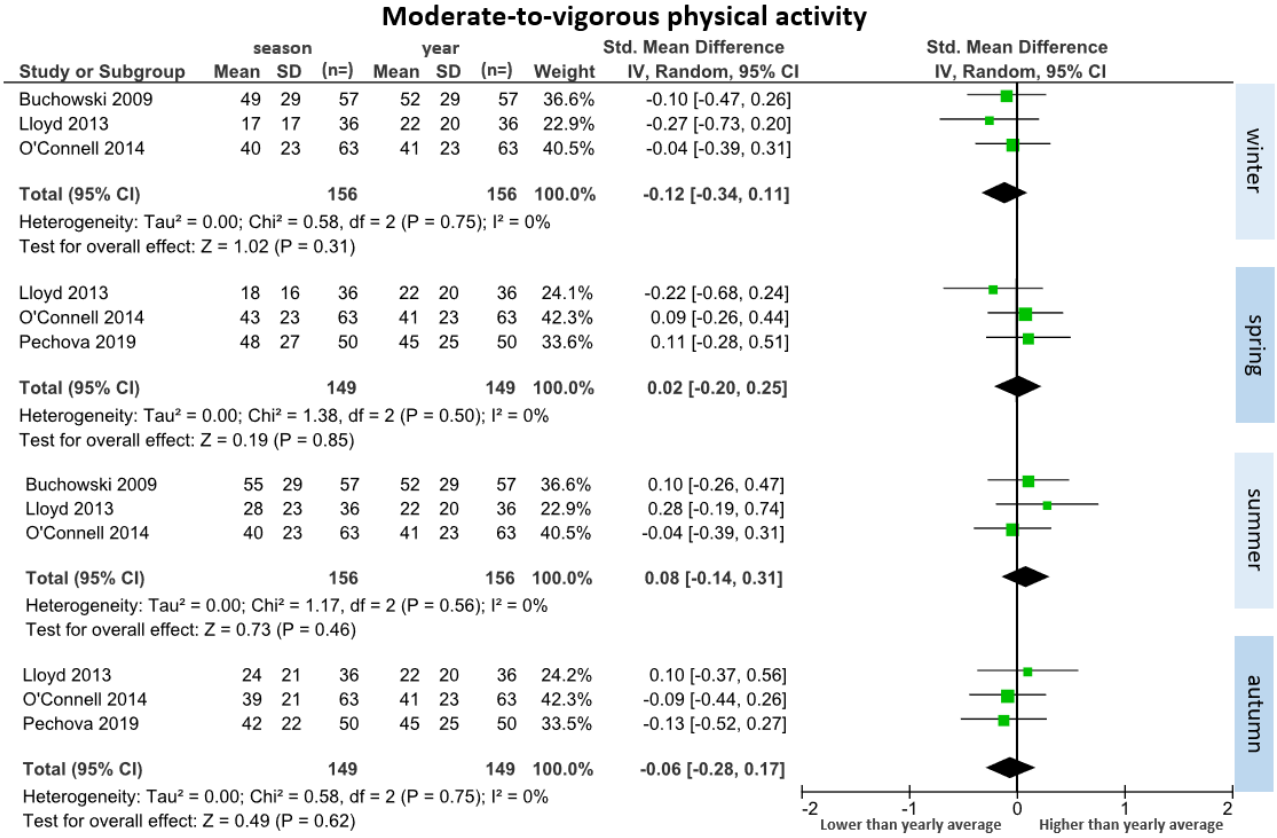


Figure 2.6 - Forest plot of daily minutes of moderate-to-vigorous physical activity comparing seasonal means with yearly mean

Ramadan (n = 4 studies)

Four studies explored daily activity patterns across Ramadan. All measured sleep duration only. For control, studies used either the week before Ramadan,[107, 108, 112] or the mean of a night before and after Ramadan.[109] The overall SMD was non-significant when comparing sleep duration during Ramadan to pre/post Ramadan (SMD = -0.47 [95% CI: -1.05 to 0.10]). There was a trend towards less sleep during Ramadan than on the control nights (WMD = 64 minutes/day). Substantial heterogeneity was observed between studies (I^2 = 82%). See Figure 2.7 for further detail.

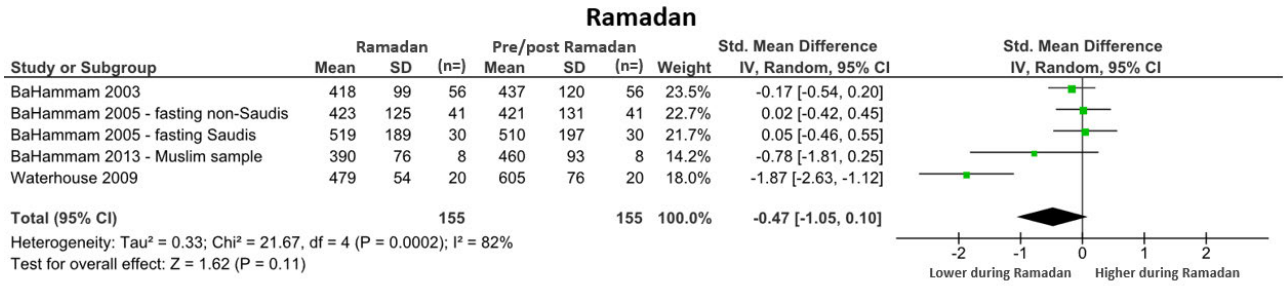


Figure 2.7 - Forest plot of daily minutes of sleep comparing during Ramadan with pre/post-Ramadan

Vacation (n = 1 study)

One study[95] explored the effect of vacationing away from home on sedentary behaviour, light physical activity and moderate-to-vigorous physical activity. Participants engaged in significantly more daily minutes of light physical activity on vacation than before (104 minutes [SD = 88 minutes] vs.71 minutes [SD = 74 minutes], p<0.001)) and after vacation (104 minutes [SD = 88 minutes] vs. 68 minutes [SD = 73 minutes], p<0.001)). This study reported a statistically non-significant trend for participants to have engaged in less daily minutes of sedentary behaviour (215 minutes [SD = 99 minutes]) compared with before (252 minutes [SD = 132 minutes]) and after vacation (251 minutes [SD = 131 minutes]), and a statistically non-significant trend to have engaged in less daily minutes of moderate-to-vigorous physical activity during vacation (29 minutes (SD = 35 minutes) compared to before (50 minutes [SD = 81 minutes]) and after vacation (41 minutes [SD = 46 minutes]).

Daylight saving time (n = 1 study)

One study [111] explored the impact of the change in daylight saving time on sleep, measuring sleep time at both the autumn transition out of daylight saving time and the spring transition into daylight saving time. In the week after the autumn transition out of daylight saving time, participants slept significantly less (25 minutes per day less, p<0.05) than during daylight saving time (365 minutes vs 340 minutes). In the week after the spring transition into daylight saving time, participants slept significantly more (28 minutes per day more, p<0.05) than before daylight saving time (340 minutes vs 368 minutes).

2.5 Discussion

2.5.1 Principal findings

This systematic review has brought together current evidence regarding annual rhythms in adults' daily movement behaviours and examined key temporal factors which may influence these rhythms. Results reveal only a handful of studies identified per temporal factor, mostly involving small sample sizes. Regardless, several trends emerged. Sleep appeared to be higher during autumn and winter, outside of Ramadan and after the transition into daylight saving time. Sedentary behaviour also appeared higher during autumn and winter, and during non-vacation periods. Light physical activity was higher during spring and summer and whilst on vacation, and moderate-to-vigorous physical activity appeared to be higher during spring and summer, and during non-vacation periods.

Seasonal effects on movement behaviours (particularly sleep) was the most commonly explored temporal factor. The meta-analyses were generally non-significant (except for light physical activity), however methodological factors may have contributed to this. Many studies used self-reported tools, which are known to have modest validity[113] and may in turn have limited the ability to accurately detect change over time. Secondly, study populations were small (especially for the sedentary behaviour, light physical activity and MVPA meta-analyses). However, the direction for change in movement behaviours across seasons were generally consistent across studies, and varied in the expected directions, suggesting that the non-significant trends may be real.

Results suggested sleep duration was approximately half-an-hour less in summer compared with autumn. This may influence health outcomes, particularly if sleep totals fall outside the optimal range for positive health outcomes of seven to eight hours.[114] For example a one-hour decrease in sleep below seven hours is associated with a 6% increase in all-cause mortality, an 11% increase in cardiovascular disease risk,[114] and a 9% increase in obesity risk.[115] Results suggested that sedentary behaviour is around 30 minutes higher in winter, relative to spring. It is questionable whether this would impact health. However, it was coupled with lower light physical activity (45 minutes less, relative to summer) and less moderate-to-vigorous physical activity (5 minutes less, relative to summer), which is likely to be of sufficient magnitude to have health consequences. For example, a one minute per day increase in

moderate-to-vigorous physical activity has been associated with a 2% decrease in all-cause mortality.[116] It has been suggested that as little as 15 minutes' extra light physical activity, or 5 minutes' extra moderate-to-vigorous physical activity, has a positive effect on all-cause mortality and cardiovascular disease.[117]

It is important to consider that season interacts with climate and daylight hours differently in different geographic regions. Almost all seasonal studies included in this review took place in temperate climate locales in the mid-latitudes (between 23° and 66°) of the northern hemisphere. Temperate climates are characterised by mild-to-warm summers and cool-to-cold winters with moderate yearly rainfall.[118] Mid-latitudes have distinct differences in daylight hours between seasons of approximately four to eight hours between winter and summer. Only a single study sample originated in a tropical climate and latitude (Ghana).[99] Given the small number of studies in this review, it is not possible to disentangle the effects of season, climate and daylight hours. Temperate climates dominate the evidence presented here, and further research in tropical and subpolar regions is warranted.

Whilst this review sought studies examining various cultural, religious and festive periods', all eligible studies of this type related to Ramadan only, and its impacts on sleep. Ramadan is an example of a periodic change to typical lifestyle patterns. Specifically, Ramadan is a spiritual disciplinary practice, where people observing Ramadan do not eat or drink during daylight hours, changing usual mealtimes, along with usual bedtimes and wake times, and therefore changes in movement behaviours could be expected. Additionally, during this month, people are reportedly less active during daylight hours[119] however none of the included studies examined physical activity during Ramadan. Across studies, participants observing Ramadan generally went to bed and woke later, with the delay in bedtime more pronounced than wake-time. Whilst there was a trend towards less sleep during Ramadan, the weighted mean sleep duration of 7 hours and 25 minutes falls within recommended levels of 7+ hours per night[84]. It should be noted that Ramadan is the ninth month of the Islamic calendar, which is 10-12 days shorter than the Gregorian calendar, therefore over several years, Ramadan will occur across all seasons. It is possible the trends observed in sleep time across seasons may interact with Ramadan differently depending on the season, with shorter winter days allowing for an extended window to consume meals, impacting less on usual sleep times. Of the studies exploring Ramadan, three were conducted in Saudi Arabia, and one in Libya. Both countries

are located at a similar latitude (approximately 16-33°), experiencing similar daylight hours across the year. Across the four included studies, Ramadan occurred between late Summer and mid-winter. While changes to sleep routine during Ramadan may be unaffected by seasonal changes at latitudes with small fluctuations in daylight hours across the year, future research in different locations is warranted.

The single study exploring daylight saving time transitions reported a significant change in sleep duration of approximately half-an-hour after each transition, with less in autumn and more in spring. It is worth noting duration at all time points fell below recommended levels of sleep per night of 7+ hours.[84] The immediate one-hour shift in clock time requires an adjustment period for our internal biological clocks to reset to the new timing of daylight hours, accounting for the immediate disruptions to sleep duration.[120] It is likely the observed changes in sleep duration return to pre-transition levels in following weeks, however further research for longer periods is needed to examine this. Further studies are needed before conclusions can be made about the impact of daylight saving time transitions.

The final periodic temporal factor explored was vacation periods where again, only a single study was found. This study suggested participants on vacation got less moderate-to-vigorous physical activity and more light physical activity and sedentary time. Further research is needed to allow for the impact of vacations on movement behaviours to be understood. Additionally, future studies should explore movement behaviour intentions for vacation periods as it may be a risk factor for poor movement behaviour during vacation. The location or time of year when participants went on vacation was not reported, and thus it is important to consider that season may be a confounding factor.

2.5.2 Implications

This review identified trends towards negative changes in daily movement behaviours during several periods. Results suggest physical activity interventions may be needed during winter and autumn months where activity levels decline. Efforts could focus on alternate exercise options for these periods, such as indoor or home-based exercise routines, along with the provision of indoor or sheltered environments within the community to combat the environmental barriers during these colder, wetter and darker periods. Interventions promoting regular movement during winter and autumn could also target sedentary

behaviour. Periodic temporal factors such as observing religious practices have potential to provide spiritual, physical and/or mental health benefits which would suggest these periods may not be the optimal time for movement behaviour intervention. Further research is needed to understand whether there are significant and lasting effects on usual movement behaviours resulting from periodic temporal factors. Opportunities may exist to promote pre-emptive behaviour changes, to counteract the effects of these periodic temporal factors if those effects are found to be impactful on health. For example, increased physical activity could be encouraged in the lead up to vacation or moving bedtime earlier before the autumn daylight saving time transition.

2.5.3 Strengths and limitations

This is the first systematic review and meta-analysis of its kind. Several strengths to this systematic review include: , the search strategy was rigorous and designed in consultation with an academic librarian, and followed PRISMA guidelines[90]; study screening, data extraction and risk of bias were all performed in duplicate, increasing accuracy and trustworthiness of results.

A key limitation of the review was the relatively small number of studies exploring each of the four included temporal factors, ranging from one study each for daylight saving time and vacation, to eleven studies for season. Most studies had small sample sizes (n = 60 or less in 14 studies). The sleep meta-analyses were dominated by a single study with a comparatively large sample (n = 960). Only one of the included studies reported the 24-hour day, with a large portion of studies measuring sleep only. Limiting to English language studies may have reduced the variety of temporal patterns explored, specifically cultural or religious events in non-English speaking countries. Only a limited number of countries were included, each with their own seasonal and daylight hour patterns, therefore findings may not be representative of countries not explored in this review.

2.5.4 Future recommendations

This systematic review highlights the limited number of cohort studies exploring annual patterns of activity. Future research with larger sample sizes, in more diverse geographic areas, and using high quality movement behaviour measurement methods, are needed. Very little research has examined changes in daily movement behaviours during festive and cultural

periods. Additionally, no studies have explored the interaction between temporal factors. Changes in a particular behaviour must be necessarily compensated by a change in another behaviour, given that there are 24 hours in a day. Methodologies which measure multiple movement behaviours simultaneously, ideally using a 24-hour measurement approach, are needed.

2.6 Conclusion

This study examined current research exploring annual rhythms in adults' daily movement behaviours and the key temporal factors which may influence these rhythms. Several trends were observed across each temporal factor including more sleep in autumn, winter and outside Ramadan, more sedentary behaviour in autumn and winter, and more light physical activity and moderate-to-vigorous physical activity in spring and summer. These trends highlight potential at-risk periods of negative movement behaviours (decline in sleep and physical activity, increase in sedentary behaviour) which may inform the timing and aid the design of health promotion and interventions strategies. Only single studies for daylight saving time transitions and vacation were included, making it difficult to draw conclusions on the impact of these temporal factors. The current evidence for temporal patterns of movement behaviours and the association with temporal factors is scarce. Future research should aim to explore the 24-hour day of movement behaviours using larger samples from a greater diversity of geographic areas, while exploring a wider variety of temporal factors and the interaction of between these.

2.7 Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Funding

There is no funding to declare for this study.

Authors' contributions

T.F., C.M., R.C. and F.F. were responsible for study inception and design. T.F. conducted all database searches. T.F., C.N., R.L. and R.V. were responsible for screening of articles, data extraction and quality assessment. R.C. acted as a third independent reviewer for resolving conflicts in screening and quality assessment. T.F. was responsible for data transformation. T.F. and C.M. were responsible for meta-analysis of the data. T.F. led manuscript writing while C.M., R.C. and F.F. provided substantive feedback. All authors read and approved the final manuscript.

Acknowledgements

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Chapter 3

The Annual Rhythms in Adults' lifestyle and health study - methodology and candidate's contributions

This chapter introduces the Annual Rhythms in Adults' lifestyle and health (ARIA) study. My PhD candidature was completed within the framework of the ARIA study. A detailed methodology of the complete ARIA study is described along with my specific contributions to the project. A published protocol paper (of which I am a co-author) for the ARIA study is included as Appendix 3.1.[121] Data from the ARIA study are used in the subsequent three study chapters.

3.1 Background

Longitudinal studies on weight suggest the average Australian adult gains 0.5 kg per year.[122] Whilst the intra-year patterns of weight are not well understood, emerging evidence suggests that gains may be accumulated at specific timepoints within a year (e.g. the Christmas-New Year period, rather than a slow creep across the year). This suggests there is a temporal context to weight gain that should be explored further. There are a variety of health-related outcomes that may contribute to changes in weight, many of which are explored in the ARIA study. The ARIA study aimed to explore the intra-year patterns of body weight, movement behaviours, diet, mental health, wellbeing and lifestyle in a cohort of Australian adults.

3.2 Methods

ARIA is a cohort study funded by the Australian National Health and Medical Research Council (grant number APP1163338). A study protocol has been published and is included as Appendix 3.1.[121] All participants in the ARIA study provided informed, written consent prior to commencing. Ethics approval was provided by the University of South Australia Human Research Ethics committee (Protocol number: 201901). The ARIA study was registered prospectively on the Australian New Zealand Clinical Trial Registry (Trial ID: ACTRN12619001430123).

3.2.1 Setting and participants

375 community-based adults were recruited from the greater Adelaide metropolitan area in South Australia. Recruitment occurred in two ways. Firstly, all parents of the 380 primary school-aged children enrolled in the cohort study *Life on Holidays* were invited to participate, making up the participants in cohorts 1 and 2.[123] Secondly, parents of primary school-aged children were recruited from the general community via digital advertising (i.e. social media posts and paid digital advertisements) and through community notice boards. These participants make up cohort 3.

Inclusion criteria were: 18 to 65 years old, a parent or guardian of a child enrolled in Life on Holidays or a parent or guardian of a child 5 to 12 years old, residing in the greater Adelaide metropolitan area, having access to a Bluetooth-enabled mobile device or computer and having home Wi-Fi internet, understanding written English, and being ambulant. Exclusion criteria were: pregnancy, having an implanted electronic medical device, or experiencing or receiving treatment for any life-threatening condition which impacts daily lifestyle and health.

Participants were enrolled in the study across two waves and remained in the study for 13 continuous months: wave 1 commenced on the 1st of December 2019 and concluded on the 31st of December 2020, and wave 2 commended on the 1st of December 2020 and concluded on the 31st of December 2021 (see Figure 3.1).

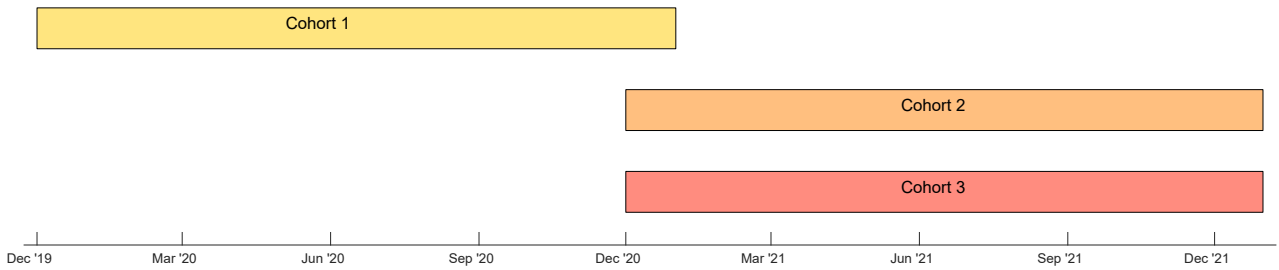


Figure 3.1 - Timeline of cohorts' participation in the ARIA study

Notes: Cohorts 1 and 2 are parents of children in the Life on Holidays study. Cohort 3 are parents recruited from the general population.

Eligible and consenting participants received a single home visit by a researcher between August and November of the year commencing the study. At this visit, a baseline survey was completed, height was measured and Fitbit devices were provided. Participants were given a Fitbit Charge 3 activity tracker and Fitbit Aria 2 or Aria Air smart body weight scale (Fitbit Inc., San Francisco, CA, USA) and instructed in their use. Participants were assisted to create Fitbit accounts and link their devices. They were then assisted to link their Fitbit user accounts to custom-built data collection software called "Fitnesslink" (created for the purpose of the ARIA study by the Adelaide-based software development company, Portal Australia).

Beyond the initial home visit, the only contact participants had with researchers for the duration of the study was receiving follow-up surveys, unless they required technological support or where compliance was an issue (e.g. not syncing Fitbit devices). During the study,

FitnessLink was used to monitor Fitbit device syncing compliance via an online dashboard. Twice-weekly checks were completed and text messages sent and/or follow up phone calls made to participants whose activity or weight data were not synced within the preceding five days. Follow-up surveys were sent via SurveyMonkey web-based software (Momentive Inc., San Mateo, California, USA). Participants were sent reminder text messages and/or phone calls when surveys were not completed within the first week, with surveys remaining open for three weeks. Upon completion of the 13-month study, participants were allowed to retain their Fitbit devices and received a $100 honorarium.

3.2.2 Variables

Health-related variables were captured by either surveys or devices. Participants completed a baseline survey prior to commencing the study, along with eight follow-up surveys spread throughout the study period (see Figure 3.2). The same survey questions were consistent across all follow-up surveys. Fitbit devices were used daily for the duration of the study.

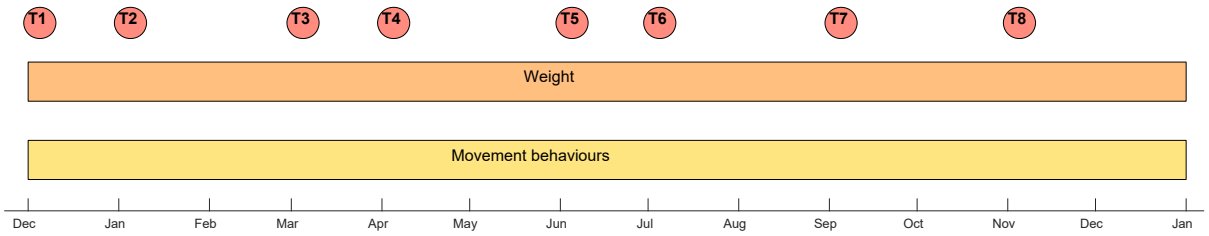


Figure 3.2 - Timeline of study measures

Notes: Red circles indicate survey distribution dates. T1 to T8 = timepoints 1 to 8. Weight was measured daily, and movement behaviours were measured continuously, (i.e. 24 hours per day).

Baseline variables

The following variables were captured in the baseline survey: date of birth, sex, country of birth, indigenous status, marital status, number of adults and children at home, highest education level, occupation, typical work pattern, combined gross household income, number of motor vehicles at home, screen availability (e.g. television, gaming equipment), parenting style, meal time structure, smoking status, presence of common chronic conditions, sleep chronotype and routineness.

Baseline height was measured using a stadiometer (Leicester Height Measure MKII) according to the International Society for the Advancement of Kinanthropometry assessment procedures.[124]

Ongoing measures

The following variables were measured at baseline and throughout the study period:

Body weight

Body weight was measured using the Fitbit smart scale (Fitbit Inc., San Francisco, CA, USA). Participants were asked to weigh themselves daily, preferably at the same time of day, wearing minimal clothing, before eating and after toileting. Daily weight data was synced to the participant's user account, and data collected remotely via Fitnesslink software.

Daily movement behaviours

Daily movement data was measured using the Fitbit activity tracker. Participants were asked to wear the device continuously on their non-dominant wrist, except for during water-based activities (e.g. swimming and showering) or whilst charging, and to sync their device at least every 5 days. Minute-by-minute data were collected remotely via Fitnesslink software. Each minute was categorised by Fitbit's proprietary algorithm as either sleep, sedentary behaviour, light physical activity, moderate physical activity or vigorous physical activity. Where minutes were classified as sedentary (default setting where no activity detected) AND heart rate data were missing, they were classified as non-wear. Fitbit wearable devices have demonstrated acceptable validity for measuring sleep duration (compared to polysomnography: Charge 2 sensitivity = 0.96, specificity = 0.61;[125] Flex r = 0.97[126]), sedentary behaviour (compared to ActivPAL: Charge 3 ICC = 0.94 (95% CI: 0.92–0.96[127])), light physical activity (compared to Actigraph: Flex did not significantly differ in daily totals[128]) and moderate-to-vigorous physical activity (compared to Actigraph: Charge 2 ICC = 0.69 (95% CI: 0.35–0.87)[129], Flex r = 0.73[128]).

Dietary intake

Dietary intake over the month prior to each survey timepoint was captured using an online survey called the Dietary Questionnaire for Epidemiological Studies (DQES v3.2, Cancer

Council Victoria).[130] The DQES has been shown to have good reproducibility and also good agreement when compared to weighed food records.[131, 132]

Recreational pursuits

Self-reported recreational physical activities were measured using items from the How Areas in Brisbane Influence Health and Activity (HABITAT) study.[133] The items were modified to ask the participant about activities undertaken over the previous month. Participants reported how often they performed 15 different activities, including running, water activities or sports, using a 5-point scale. Additionally, participants reported the number of hours per day they watched a television or used an electronic device on a typical weekday and weekend day.

Mental health and wellbeing

Symptoms of depression, anxiety and stress were measured using the short form of the Depression Anxiety Stress Scale (DASS-21).[134] DASS-21 has been shown to have high reliability, adequate construct validity and good convergent and discriminant validity when compared with other validated measures.[135, 136] Quality of life was assessed using the World Health Organization Quality of Life assessment 26-item version (WHOQOL-BREF).[137] WHOQOL-BREF measures four domains, including physical health, psychological health, social relationships and environment. The tool has been shown to have acceptable test-retest reliability, internal consistency, content validity and discriminant validity.[137-139]

Work and vacation status

Participants reported their average weekly work hours outside the home over the past month. Participants also reported any vacations they had taken since the last survey, the start and end dates of the vacation, if the vacation was at home or away, and the main activity on vacation (e.g. camping, rest and relaxation).

3.2.3 Power calculation

Power calculations for the ARIA study were performed by the study's statistician, Professor Adrian Esterman. Current sample size software is unable to accurately calculate the required sample size owing to the complexity of the multilevel model required to address the aim of this study. Instead, a required sample size estimate was produced using a multivariable linear regression model, with conservative estimates and adjusting for clustering within families. The

initial estimate suggested a sample size of 226 would provide 90% power to detect an r^2 of 0.1 attributed to 10 independent variables when the significance level was 0.025. Additionally, data were potentially clustered in families, with an estimated average cluster size of 1.5 and an ICC of 0.7. This design effect equals 1.35, giving a required total of 305 participants. When allowing for withdrawal of participants and loss to follow-up, a final estimated sample size would be 371. Therefore, a target sample size of 375 was deemed to provide sufficient power.

3.2.4 Statistical analyses

The ARIA study is a complex, multivariate dataset which is being explored across a variety of study aims, with a variety of statistical approach beyond those detailed in the following chapters. Statistical analyses for ARIA studies included in this thesis are detailed within each chapter.

3.3 Candidate's contributions

This section will detail my contributions to the conduct of the ARIA study. I commenced my PhD candidature and joined the ARIA study mid-2019 when ethics approval had been initially granted but before study protocols had been finalised and before participant recruitment had commenced. My contribution has been across all stages of the study, either in a leading role or co-contributing role.

Tasks I have led:

- Writing of the standard operating procedures manual for participant home visits (see Appendix 3.5). This included writing the procedure manual and creating ancillary forms.
- Liaising and working with the software developer for Fitnesslink software to obtain Fitbit data. This included much troubleshooting of data capture issues throughout the two, 13-month data collection waves, and also post-data collection completion.
- Data cleaning and processing. A large portion of my candidature has been focused on compiling the ARIA dataset. This has involved learning to code using MATLAB software to create software programs capable of cleaning, visualising and processing over 210,000,000 minutes of activity data. Data samples of the ARIA dataset were

provided by Portal Australia and various timepoints throughout the active data collection period to facilitate programming of data processing software and identifying errors in the datasets. The final complete ARIA dataset was available to me at the beginning of March 2022. Additionally, I cleaned and processed all survey data in SPSS and compiled these data with Fitbit movement and weight data to create a master dataset comprising over 1300 variables. I also created an extensive data dictionary to accompany the master dataset. These data and the data dictionary are used in three studies include in this thesis, and also being used by an additional 13 members of the ARIA project team or members of the Alliance for Research in Exercise, Nutrition and Activity research centre for publications related to other study outcomes (e.g. weight, diet, etc.).

Tasks to which I have co-contributed:

- Training and supervising research staff to conduct home visits with participants in line with the standardised operating procedures manual.
- Conducting baseline home visits with participants.
- Weekly compliance checks via Fitnesslink software. This included follow up contact with participants and troubleshooting of devices.
- Attending and contributing to frequent ARIA meetings for project staff, the chief investigator team and external stake holders on the ARIA study advisory group. In these meeting I provided regular contributions relating to data matters and sharing preliminary results.
- Creating and contributing results to the personalised, end-of-study reports provided to all participants.
- Contributing as a co-author to manuscripts led by other ARIA team members.

Chapter 4

The annual rhythms in sleep, sedentary behaviour and physical activity of Australian adults: a prospective cohort study

This chapter is presented in manuscript format and describes the year-long patterns of movement-related behaviours of participants in the ARIA study. The aim of this study was to explore the associations between movement-related behaviours and temporal cycles such as the day of the week and season, and temporal events such as the Christmas-New Year period and daylight savings time transitions. A signed Statement of Authorship form for the relative contribution of all authors to this manuscript is in Appendix 4.1.

Citation:
Ferguson T, Curtis R, Fraysse F, Olds T, Dumuid D, Brown W, Esterman A, Maher C. The annual rhythms in sleep, sedentary behaviour and physical activity of Australian adults: a prospective cohort study. Journal of Sport and Health Science. 2022; *Manuscript under review.*

4.1 Abstract

Background

Sleep, sedentary behaviour and physical activity have fundamental impacts on health and well-being. Their sociodemographic and environmental correlates are well understood. Far less is known about how these movement-related behaviours vary across the year. The aim was to explore how movement patterns change across days of the week and seasons, and describe movement patterns across a full year and around specific temporal events (e.g., Christmas/New year, daylight saving time transitions).

Methods

This cohort study included 368 adults from Adelaide, Australia (mean age = 40.2 years [SD = 5.9]) who were asked to wear Fitbit activity trackers 24 hours a day for 12 months. Minute-by-minute data on sleep, sedentary behaviour (SB), light physical activity (LPA), and moderate-to-vigorous physical activity (MVPA) were collected. Temporal patterns of each behaviour were analysed descriptively. Associations with specific temporal cycles (day of the week, season) and events (Christmas-New Year, daylight saving time [DST] transitions) were explored using multi-level mixed-effects linear regression.

Results

Movement patterns varied significantly ($p<0.05$) by day of the week and season, and at annual events. Sleep was longer on weekends relative to weekdays (+32 min/day), during autumn and winter relative to summer (+4 and +11 min/day), and over Christmas-New Year relative to the week before the holiday (+24 min/day), and shorter in the week after DST ended (April) relative to the week prior (-7 min/day). Sedentary behaviour was longer on weekdays, during winter, after Christmas-New Year and after DST ended (+45, +7, +12 and +8 min/day respectively). LPA was shorter in autumn, winter, and during and after Christmas-New Year (-6, -15, -17 and -31 min/day respectively). Finally, there was less MVPA on weekends and during winter (-5 min/day and -2 min/day respectively). Across the year, 14-day moving averages varied by 30 min/day for sleep (6% of mean sleep duration), 35 min/day for sedentary behaviour (6%), 43 min/day for LPA (14%) and 7 min/day for MVPA (21%).

Conclusions

Movement behaviour fluctuations associated with temporal events are overlaid on a weekly and seasonal rhythm. Understanding these fluctuations may inform the design and timely implementation of health promotion campaigns and interventions.

Keywords

Sleep, sedentary behaviour, physical activity, time use, annual rhythms

4.2 Introduction

Time use during a 24 hour day can be divided into three broad categories: sleeping, being sedentary and being active.[140] The amount of time spent in each influences health.[141] International guidelines suggest adults should engage in the equivalent of 150 to 300 minutes of moderate physical activity or 75 to 150 minutes of vigorous physical activity per week, 7 to 9 hours of sleep per night, and limit prolonged bouts of sedentary behaviour.[84, 142, 143] Emerging evidence also supports the benefits of light physical activity.[42, 43] Conversely, insufficient physical activity or sleep, and excessive sleep or sedentary time are associated with negative health outcomes, including increased mortality and morbidity, increased incidence of non-communicable chronic disease and poor mental health.[34, 42, 79, 144] Interventions are needed to improve movement patterns, and these interventions should acknowledge and address the factors which influence and constrain movement behaviours.

Allocation of time to each movement behaviour reflects a complex and dynamic interaction of internal and external factors. These include the physical environment (e.g. urban design, natural environment and weather),[145] resource availability (e.g. finances, exercise or active transport equipment, home design), time constraints (e.g. employment, care duties, unpaid work, unplanned disruptions), and physical (e.g. fitness, health status, presence of injury or disability)[146] and cognitive attributes (e.g. values, beliefs, personality, motivators and barriers). As a result, the day-to-day distribution of time is susceptible to fluctuations. Literature on intra-annual patterns is sparse.

Our recent systematic review identified 17 studies of intra-annual temporal cycles, specifically seasonal changes, and temporal events, including Ramadan, vacations, and daylight saving time transitions.[71] Several key limitations with the existing evidence base were identified. Namely, a small range of temporal factors was explored in isolation, most studies did not report the full range of daily movement behaviours (94%), and generally only short measurement periods were used (82% measured 2 weeks or less at each timepoint). These limitations reduce the clarity and strength of findings and increase the potential for external effects on behaviour (e.g., unseasonable weather, brief unexpected life events).

Gaining an understanding of the timing of movement patterns within a year-long cycle is important for informing the timing of interventions and health promotion initiatives. Delivering interventions and health messaging at the time they are most needed will have the greatest benefit. Further, identifying temporal events associated with unfavourable movement behaviours may afford additional opportunities for positive health action.

Our aim was to explore how daily movement patterns of Australian adults vary across days of the week and seasons, over a full year and around specific temporal events (e.g., Christmas-New Year, and daylight saving time transitions).

4.3 Methods

4.3.1 Study design

Data used in this study were collected for the *Annual Rhythms In Adults' lifestyle and health* (ARIA) prospective cohort study. ARIA followed a cohort of Australian adults, collecting data on 24-hour movement behaviours, dietary patterns, body weight, and wellbeing. Further details of the study protocol have been published elsewhere.[121]

Ethics approval was provided by the University of South Australia Human Research Ethics committee (Protocol number: 201901). The study was prospectively registered on the Australian New Zealand Clinical Trial Registry (Trial ID: ACTRN12619001430123). All participants provided informed, written consent prior to commencing in the study.

4.3.2 Setting and participants

375 community-based, middle-aged adults were recruited from Adelaide, South Australia for the ARIA study. Participants were either parents of children enrolled in a separate cohort study called *Life on Holidays* [123] (cohorts 1 and 2), or parents of primary school children recruited from the community via general advertising (i.e. social media posts, paid digital advertisements, community notice boards) (cohort 3).

Study enrolment occurred in two waves: cohort 1 commenced on 1/12/2019, and cohorts 2 and 3 commenced on 1/12/2020. Each wave remained in the study until the end of the following December (31/12/2020 and 31/12/2021 respectively).

Inclusion criteria included: 18 to 65 years old; parent/guardian of a child enrolled in Life on Holidays study or a parent/guardian of child aged 5 to 12 years at time of enrolment; residing in greater metropolitan Adelaide; access to a Bluetooth-enabled mobile phone or computer and home internet; understand English language; and ambulant. Reasons for exclusion included: being pregnant; having an implanted electronic medical device; or receiving treatment for, or experiencing any life-threatening condition which impacted daily lifestyle and health.

A researcher visited eligible and consenting participants at their homes between August and November in the year of commencing the study. During this visit, height was measured, and participants completed a survey containing baseline demographic, health and lifestyle items. Participants were provided with a Fitbit Charge 3 fitness tracker and Fitbit Aria body weight scale (Aria 2 or Aria Air scale, Fitbit Inc., San Francisco, CA, USA) and instructed in the use of each device.

During the study, participants used the Fitbit devices daily and completed eight follow-up surveys of wellbeing and diet (not used in the current analysis). On completion of the study, participants received an honorarium of $100 and were able to keep the Fitbit devices.

4.3.3 Variables

Daily 24-hour movement behaviours

Objectively measured minute-by-minute movement behaviour data were collected via a wrist-worn Fitbit Charge 3 activity tracker (Fitbit Inc., San Francisco, CA, USA). The device was worn continuously (24-hours) on the participants' non-dominant wrist, except whilst charging or during water activities. Participants were directed to sync their devices to their linked Fitbit user account frequently (minimum every 5 days). Fitbit data were collected remotely via "Fitnesslink" software (Portal Australia, Adelaide, Australia), purpose-built for the study.

Every minute was classified as either sleep, sedentary behaviour, light physical activity, moderate physical activity, vigorous physical activity or non-wear time, using Fitbit's proprietary algorithm. Fitbit devices have shown acceptable validity for sleep duration,[125, 126] sedentary behaviour[127] and physical activity.[128, 129]

Temporal cycles and events

Temporal cycles explored statistically included day of the week and season. Temporal events included Christmas-New Year period and daylight saving time transitions.

Participant characteristics

Participant baseline data included age, sex, chronic conditions, sleep chronotype, smoking status, indigenous status, country of birth, marital status, number of adults and children in household, highest education level, occupation, hours of work per week outside the home, and combined gross household income.

4.3.4 Data treatment

Daily minute totals (i.e., midnight-to-midnight) for sleep, sedentary behaviour, light physical activity and moderate-to-vigorous physical activity for each participant day were calculated. Moderate-to-vigorous physical activity was calculated as the daily sum of moderate physical activity and vigorous physical activity. A day was defined as valid if it included at least 18 hours of movement data and included a period of sleep. Participants were included if they had at least 2 valid days.

4.3.5 Statistical analysis

Multilevel mixed effects linear regression modelling with random intercepts (to adjust for the non-independence of the data and to account for nesting of repeated measures within individuals, individuals within families, and families within waves) was used to compare movement behaviours across days of the week, seasons, and 'events'. Movement behaviours were the dependent variables, with one included per model. Day of the week, season, and 'events' (holiday period and daylight saving time), were included as fixed effects in their respective models. Days of the week analyses compared Monday with Tuesday through to Sunday. Season compared mid-summer (January) with the middle month of each remaining season (autumn = April, winter = July, spring = October). Christmas-New Year periods

compared the 7 days prior to Christmas (18th - 24th December) to the Christmas-New Year period (25th Dec – 1st Jan) and the 7 followings days (2nd – 8th Jan). Daylight saving time analyses compared the 7 days prior to each transition day with the 7 following days (including the day of transition and the next 6 days). Daylight saving time started (clocks shift 1 hour forward) on the 4th October 2020 and 3rd October 2021, and ended (clocks shift 1 hour backward) on 5th April 2020 and 4th April 2021 during the study period. The regression coefficients for each comparison were used to identify the difference in daily minutes of each movement behaviour associated with a change in day, season or timepoint respectively.

Annual rhythms in each movement behaviour were examined as a change from the yearly mean, using a 14-day moving average. To represent an annual (12-month) cycle, annual rhythm graphs represent the first 12 months of study participation for all participants (wave 1 = December 2019 to November 2020 inclusive, wave 2 = December 2019 to November 2021 inclusive). The intercalary day of 29th February in 2020 was excluded for wave 1.

All statistical modelling was completed in Stata 17 (StataCorp, College Station, TX, USA) with statistical significance set at 0.05, and all graphs were generated using MATLAB version 9.11 (MathWorks, Natick, MA, USA).

4.4 Results

4.4.1 Participants

Movement behaviour data were available for 368 participants (see Table 4.1). Their average age was 40 years (range = 27-65 y). The majority were in the overweight or obese BMI categories (34% and 35% respectively), married or in de facto relationships (85%) and had two or more children (90%). Almost half the participants had a university education (48%).

Table 4.1 - Participant characteristics at baseline (N = 368)

	Mean	(SD)
Age (years)	40.2	(5.9)
Weight (kg)	84.0	(20.5)
Height (cm)	170.4	(9.5)

	n	(%)
Sex		
Female	209	(56.8)
Male	159	(43.2)
Weight status		
Underweight	1	(0.3)
Normal	114	(31.0)
Overweight	124	(33.7)
Obese	129	(35.1)
Chronic illness		
None	163	(44.3)
Single	107	(29.1)
Multiple	98	(26.6)
Sleep chronotype		
Definitely a morning type	82	(22.3)
More a morning type than evening type	122	(33.2)
More an evening type than morning type	111	(30.2)
Definitely an evening type	53	(14.4)
Smoker	34	(9.2)
Aboriginal and Torres Strait Islander peoples	4	(1.1)
Born in Australia	279	(75.8)
Marital status		
Married/de facto	313	(85.1)
Separated, divorced or widowed	29	(7.8)
Never married	26	(7.1)
Adults in household		
One	38	(10.3)
Two	305	(82.9)
Three	17	(4.6)
Four or more	7	(1.9)
Children in household		
One	36	(9.8)
Two	195	(53.0)
Three	95	(25.8)
Four or more	42	(11.5)
Education		

Year 10 or less	17	(4.6)
Year 11 - 12	49	(13.3)
Certificate/Diploma	125	(34.0)
University degree	177	(48.1)
Occupation		
Managerial and professional	148	(40.2)
Technical and clerical	77	(20.9)
Community, personal service, sales	67	(18.2)
Machinery operators, drivers, labourer	14	(3.8)
No job/other	62	(16.8)
Hours worked per week		
None	55	(14.9)
<15	25	(6.8)
15-35	119	(32.3)
36+	169	(45.9)
Household income (Australian Dollars)		
< $50,000	37	(10.1)
Between $50,000 and $99,999	111	(30.2)
Between $100,000 and $199,999	176	(47.8)
≥$200,000	44	(12.0)

4.4.2 Movement behaviour data

Data from 92,912 valid days were analysed, with an average of 252 (SD = 116) valid days per participant. The average percent of valid daily participant data was 63.7% (SD = 6.6%). Across the whole year, daily averages for each movement behaviour were 8 hours and 10 minutes of sleep (SD = 88 min), 10 hours and 18 minutes of sedentary behaviour (SD = 121min), 5 hours of light physical activity (SD = 92 minutes) and 32 minutes of moderate-to-vigorous physical activity (SD = 38 minutes).

4.4.3 Day of the week

Daily sleep (midnight-to-midnight) varied by approximately 66 min/day (13.5%) across the week, with the shortest sleep on Fridays (-19 min/day (-3.9%), $p<0.001$) and longest on Sundays (+47 min/day (+9.5%), $p<0.001$) relative to Mondays (see Figure 4.1 and Appendix 4.2). There was a clear pattern for sleep to gradually decrease as the week progressed from Monday to Friday, followed by a sharp increase in sleep on the weekend days.

Sedentary behaviour varied by approximately 60 min/day (9.6%) across the week, with the least on Sundays (-51 min/day (or -8.2%), $p<0.001$) and most on Wednesdays (+8 min/day (+1.4%), $p<0.001$) relative to Mondays. The weekday-weekend pattern was opposite to that of sleep.

Light physical activity varied by approximately 14 min/day (4.7%) across the week. Relative to Mondays, light physical activity duration was significantly longer on Wednesdays to Saturdays, with a steady upward trajectory across these days (+2 min/day (+0.6%) on Wednesday to +14 min/day (+4.7%) on Saturday). Light physical activity on Tuesday and Sunday did not differ from Monday.

Moderate-to-vigorous physical activity varied by approximately 6 min/day (18%) across the week. Thursday, Saturday, and Sunday each had significantly more moderate-to-vigorous physical activity relative to Monday (+1 min/day, +6 min/day and +4 min/day respectively, all $p<0.01$). The remaining days did not differ from Mondays.

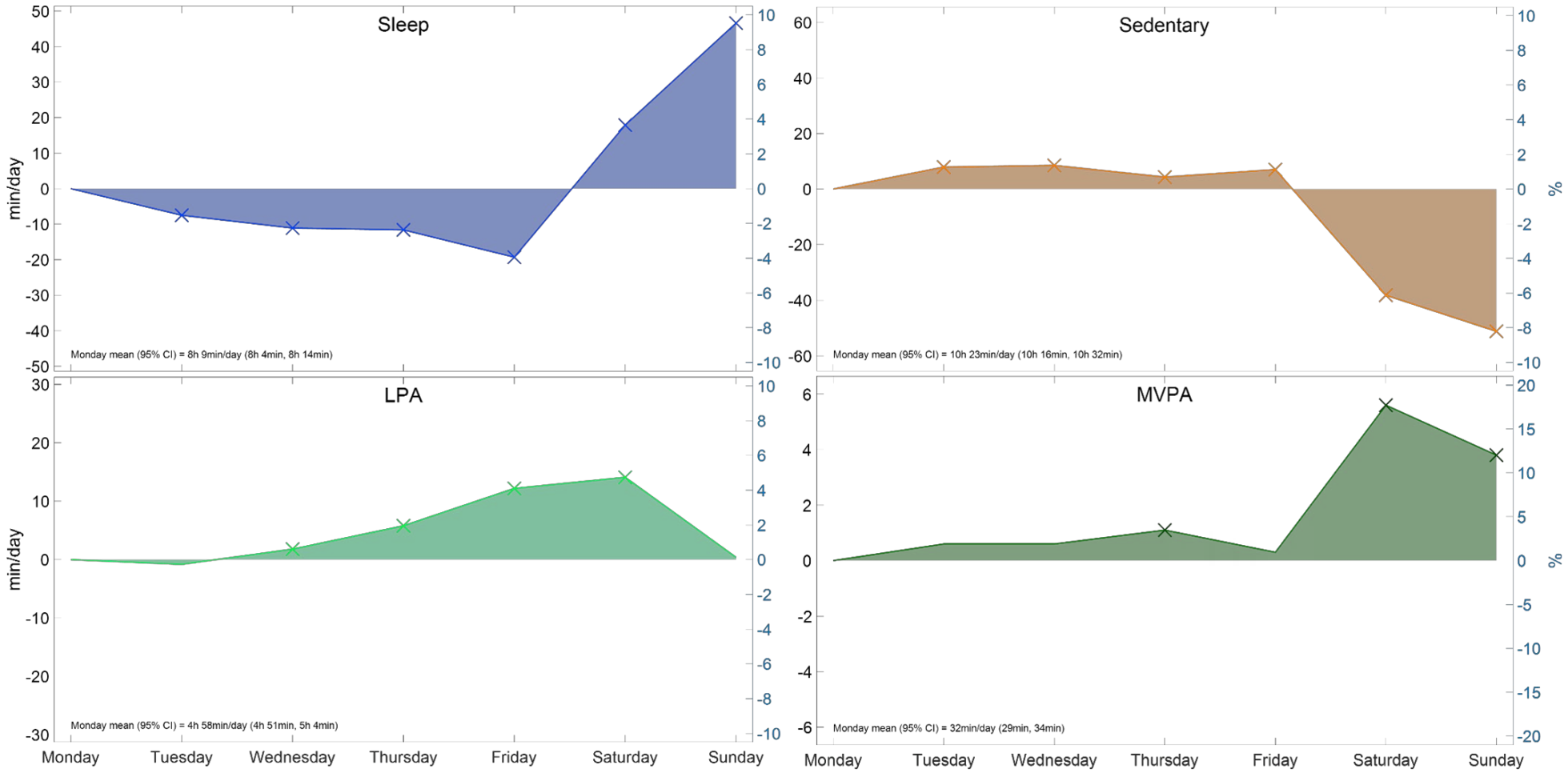


Figure 4.1 - Day of the week modelled changes, compared with Monday

Notes: LPA = light physical activity, MVPA = moderate-to-vigorous physical activity. X = significant change from Monday ($p<0.05$). Percent range (right y-axis) is +/-10% except for MVPA which is +/-20%.

4.4.4 Season

Relative to summer, sleep was 4 minutes per day longer in autumn (+0.9%, p=0.001), 11 minutes per day longer in winter (+2.2%, p<0.001), and similar in spring (Figure 4.2 and Appendix 4.3). Sedentary behaviour was similar across seasons except for winter, when it was 7 minutes per day greater than summer (+1.1%, p<0.001). Relative to summer, light physical activity was 6 minutes per day less in autumn (-2%) and 15 minutes per day less in winter (-4.9%; both p<0.001), and similar in spring. Moderate-to-vigorous physical activity was 2 minutes per day less in winter (-6.5%, p<0.001), 2 minutes per day more in spring (+4.5%, p=0.008) and similar in autumn, compared with summer.

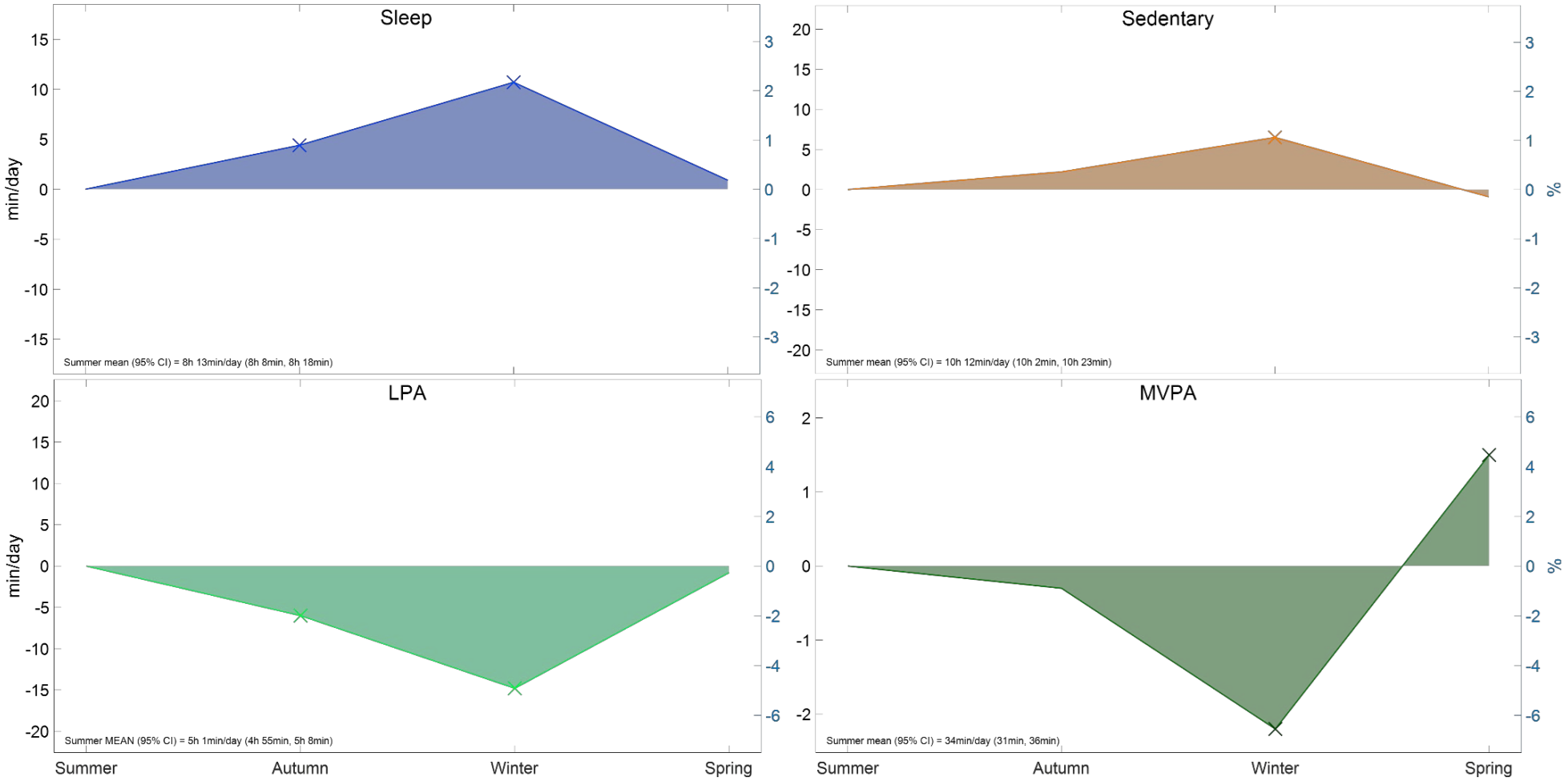


Figure 4.2 - Seasonal modelled changes as compared to summer

Notes: LPA = light physical activity, MVPA = moderate-to-vigorous physical activity. X = change from summer ($p<0.05$). Percent range (right y-axis) is +/-3% for sleep and sedentary, +/-6% for LPA and MVPA.

4.4.5 Annual change in 24-hour movement behaviours

Annual patterns in 24-hour movement behaviours are presented in Figure 4.3. Visual inspection suggested that across the year, sleep varied by approximately 30 min/day (6% of mean sleep duration). Sleep duration was generally above average during the months of April to October, and below average during the months of November to March (except for above average sleep duration in the first two weeks of January).

Sedentary behaviour varied by approximately 35 min/day (6%) across the year, though for most of the year it only varied by around ±5 min/day (±1% of yearly average). There were two clear spikes in sedentary behaviour, a one-week dip of approximately -25 min/day (-4%) around Christmas to New Year, and a one-week spike of approximately 10 min/day (+1.8%) in late July.

Light physical activity varied by approximately 43 min/day (14%) across the year. Light physical activity was generally above average from November to March, and below average from April to October. There was a notable week-long spike of approximately +23 min/day (+7.7%) around Christmas to New Year and a notable week-long dip in late July of approximately 20 min/day (-6.7%).

Moderate-to-vigorous physical activity varied by approximately 7 min/day (21%) across the year. Generally, moderate-to-vigorous physical activity varied within ±1min/day (3%) of the yearly average from December to May, was below average in June and July and above average from August to November. A week-long spike of approximately +3 min/day (+9%) occurred at the end of October, and week-long dips of approximately -3 min/day (-9%) and -4 min/day (-12%) occurred in July and August respectively.

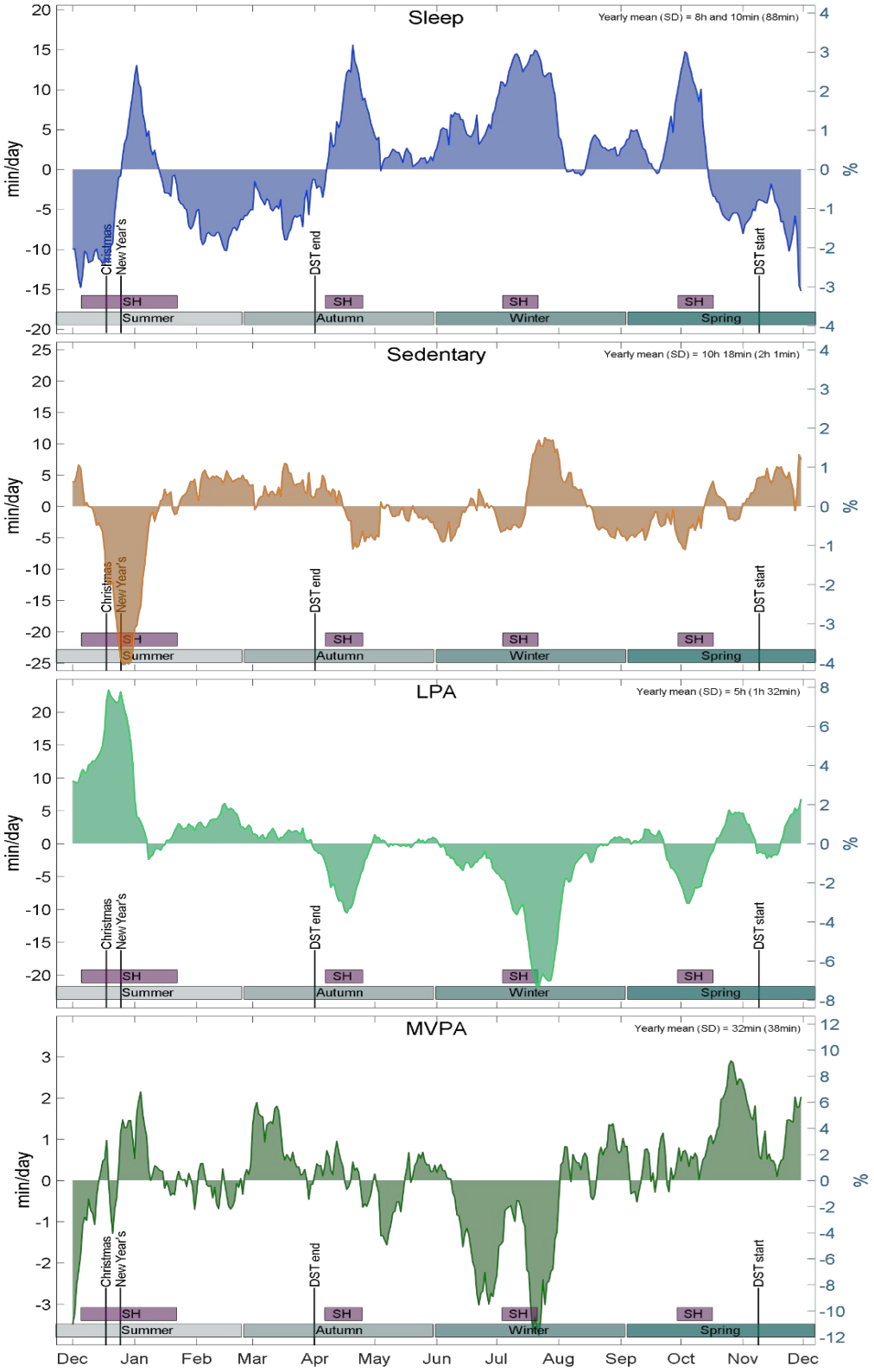


Figure 4.3 - Annual rhythms of sleep, sedentary behaviour, light physical activity and moderate-to-vigorous physical activity

Notes: Presented as change from yearly mean in minutes (left y-axis) and as a percent (right y-axis) using a centered 14-day moving average. DST end = daylight saving time ends (clocks moved back 1 hour), DST start = daylight saving time starts (clocks moved forward 1 hour), SH = school holidays.

4.4.6 Christmas-New Year holiday period

During the Christmas-New Year holiday period, sleep was 24 minutes per day longer (+5.0%, p<0.001), and light physical activity was 17 minutes per day shorter (-5.2%, p<0.001), relative to the week before the holiday period. Similarly, in the week after the holiday period, sleep was 21 minutes per day longer (+4.3%, p<0.001), light physical activity was 31 minutes per day shorter (+9.4%, p<0.001), and sedentary behaviour was 12 minutes per day longer (+2%, p<0.001), relative to the week before the holiday period (see Table 4.2).

4.4.7 Daylight saving time transitions

The weeks before and after the start of daylight saving time, when clocks shifted one hour forward, did not differ significantly for any movement behaviour. At the end of daylight saving time, when clocks shifted one hour backward, sleep was shorter in the week after by 7 minutes per day (-1.5%, p=0.009) and sedentary behaviour was 8 minutes per day longer (+1.2%, p=0.024), relative to the week before the transition (see Table 4.2).

Table 4.2 - Temporal events comparisons

Christmas - New Year				
		Coefficient	[95% conf. interval]	p
Sleep	pre (cons)	479.2	[473.0, 485.4]	
	during	**23.8**	[19.0, 28.6]	<0.001
	post	**20.7**	[15.7, 25.7]	<0.001
Sedentary	pre (cons)	597.3	[588.7, 605.9]	
	during	-4.5	[-10.3, 1.2]	0.121
	post	**12.0**	[5.9, 18.0]	<0.001
LPA	pre (cons)	331.2	[321.3, 341.1]	
	during	**-17.2**	[-21.5, -12.9]	<0.001
	post	**-31.1**	[-35.6, -26.5]	<0.001
MVPA	pre (cons)	35.5	[32.7, 38.2]	
	during	-1.8	[-3.8, 0.2]	0.079
	post	-1.6	[-3.7, 0.5]	0.130
DST start				
		Coefficient	[95% conf. interval]	p
Sleep	pre (cons)	504.8	[497.4, 512.2]	
	post	4.4	[-1.3, 10.1]	0.129
Sedentary	pre (cons)	606.3	[586.2, 626.4]	
	post	-4.3	[-11.6, 3.0]	0.244
LPA	pre (cons)	292.6	[284.1, 301.0]	

	post	-1.5	[-6.6, 3.5]	0.552
MVPA	pre (cons)	33.7	[30.7, 36.8]	
	post	-1.0	[-3.4, 1.4]	0.416
DST end				
		Coefficient	[95% conf. interval]	p
Sleep	pre (cons)	490.5	[484.1, 496.8]	
	post	**-7.2**	[-12.6, -1.8]	0.009
Sedentary	pre (cons)	619.0	[609.1, 628.9]	
	post	**7.6**	[1.0, 14.2]	0.024
LPA	pre (cons)	299.2	[291.1, 307.3]	
	post	-0.5	[-5.0, 4.1]	0.839
MVPA	pre (cons)	32.9	[30.1, 35.7]	
	post	-0.2	[-2.4, 2.0]	0.857

Notes: Results of multi-level mixed-effects linear regression analyses (one model per movement behaviour, per comparison). Models adjusted for nesting of observations within participants, within families, within study waves. Bold values indicate p<0.05. Cons = constant, LPA = light physical activity, MVPA = moderate-to-vigorous physical activity. *Christmas - New Year*: pre = 7 days prior to 25th December, during = 25th December to 1st January, post = 7 days post 1st January. *Daylight saving time (DST) end*: clocks shifted backward 1 hour on 5/4/20 and 4/4/21, pre = 7 days prior to transition, post = 7 days post. *DST start*: clocks shifted backward 1 hour on 4/10/20 and 3/10/21, pre = 7 days prior, post = 7 days post.

4.5 Discussion

Our aim was to explore how daily movement patterns of Australian adults vary across temporal cycles and events. This cohort study interrogated 12 months of movement behaviour data to understand day-to-day and seasonal changes, and explore changes related to the Christmas-New Year and daylight saving time transition periods.

Clear fluctuations in movement behaviours were apparent at specific temporal events, in concert with a weekly and seasonal rhythm of behaviour patterns across the study period. In particular, sleep was longer on weekends, during autumn and winter, and over Christmas-New Year (approximately +32, +4, +11 and +24 min/day respectively), and shorter after daylight saving time ended (-7 min/day). Sedentary behaviour was longer on weekdays, during winter, after Christmas-New Year and after daylight saving time ended (+45, +7, +12

and +8 min/day respectively). Light physical activity was shorter in autumn, winter, and during and after Christmas-New Year (-6, -15, -17 and -31 min/day respectively). Finally, moderate-to-vigorous physical activity was shorter on weekends and during winter (approximately -5 min/day and -2 min/day respectively).

The weekday-weekend and seasonal rhythms in movement behaviours observed in this study are broadly consistent with previous literature. For example, longer sleep on weekends has been reported in previous studies.[147-149] A systematic review by Chaput et. al. provided evidence of catch-up sleep as favourable for health[150] however, Putilov et. al. concluded that it is not possible to fully recover sleep debt on weekends.[147] A pattern of more active and less sedentary weekends [151] is sometimes described as a "weekend warrior" profile,[152] which is associated with increased leisure time on non-work days.

In contrast with the findings of our recent systematic review and meta-analysis, which found that 15/16 comparisons were non-significant ($p \geq 0.05$), we identified seasonal changes in all four daily movement behaviours.[71] However, the magnitude of seasonal differences in sleep were reasonably similar in the two studies, whilst the seasonal differences in sedentary behaviour and physical activity were larger in the current study than in the systematic review. This may be due to the systematic review sample for these comparisons being roughly a third of the ARIA sample and a different comparator was used (i.e., yearly average in systematic review). Furthermore, the sample sizes of the studies included in the systematic review were relatively small (82% of samples were $n \leq 60$). A recent scoping review of seasonal variations in physical activity and sedentary behaviour reported broadly similar results to the current study, with moderate to strong evidence in support of our findings.[153] More sleep and sedentary behaviour and less physical activity during winter than in summer is likely a result of less favourable weather conditions for outdoor leisure, exercise and active transport.[145, 154] Additionally, extremes of weather (i.e. too hot, cold, wet or windy) are more likely to push people indoors where sedentary activities are more commonly performed.[155]

The societal events explored in this study identified specific timepoints of movement pattern fluctuations. Christmas to New Year's Day in Australia is a socially significant period of change in time demands. It is marked by several public holidays in short succession,[156] higher than average vacation and travel (61% of participants in this study reported one or more vacation

day during this period),[157] and reduced productivity and closures across many non-essential industries.[158] Our study appears to be the first to explore movement behaviour duration changes at this period. However, a 2000 study of holiday weight gain (including Thanksgiving) among American adults did capture participant's self-report physical activity levels.[159] About half (52%) the participants reported being "somewhat or much less active", 25% reported no change, and 23% were "somewhat or much more active". Whilst different measures, the findings are to some extent comparable with the decrease in light physical activity observed in this study.

Only one previous study appears to have looked at daylight saving time transitions. Tonetti et al. reported a much larger increase in sleep (+25 min/day) post-daylight saving time ending than this study (+7 min/day).[111] Additionally, they reported an opposite, yet similar magnitude change following the commencement of daylight saving time (+28 min/day), while our study found no change. It is important to acknowledge the differences between the two samples. The Tonetti study included a small sample of young male university students (n=14) who had an average sleep duration of 2 h/day less than the ARIA participants who were both males and females. The time demands and time-use behaviours of the Tonetti sample are likely to be very different from those of the middle-aged, generally employed parents in the ARIA sample. Beyond sleep duration, there is evidence to suggest the start of daylight saving time negatively impacts sleep quality along with indirect evidence of increases in traffic accidents attributed to fatigue alertness, ambient light changes, and/or and rushing to work.[160, 161]

4.5.1 Strengths and limitations

The main strength of this study is the collection of continuous minute-by-minute device-measured movement behaviour data over a whole year. These continuous data afford the ability to assess changes in movement behaviours due to various temporal factors at a granular level. It is a large and high-quality dataset suited to answering the research questions proposed in this study. However, there are also some limitations to the study. Firstly, the sample size limited the power of the study for exploring participant sub-groups in further detail. Additionally, data collection occurred during the COVID-19 pandemic, where changes to work patterns and access to usual active pursuits (e.g., gyms, sports leagues) were limited at times. Though, as Australia maintained an "elimination" approach to the virus (i.e., closed international and state borders, strict quarantine rules for new arrivals) for much of the study

period, there were minimal lifestyle impacts in South Australia, compared with other states and countries. Finally, the generalizability of results is unclear. It is important to acknowledge that the study took place in a temperate climate zone and may not reflect seasonal variation in other climates. Also, Australia is located in the southern hemisphere, where Christmas-New Year occurs during the summer.

4.5.2 Implications and future directions

This study has methodological implications for future research and provides clues for the future development of activity interventions. Time-use behaviours, including how and when we sleep, rest and are active are subject to "time-use inertia" where the distribution of time tends to remain fairly constant unless acted on by a disruptive force, in this case an event or a change in the phase of a temporal cycle.[162] Some of these disruptors are environmental, e.g. cold weather driving long sleep and sedentary time during winter, or social, e.g. less sedentary time on non-work days (i.e. weekends and holiday periods). This study highlights several disruptors across the year when movement behaviours trend in unfavourable directions. This information is potentially important for the optimal timing of positive movement behaviour change interventions and public health messaging. For example, we could encourage people to move more and sit less during winter, on weekdays and at Christmas-New Year, and promote sufficient sleep during weekdays and at daylight saving time transitions.

Additionally, understanding time-use disruptors and how they are associated with movement patterns has implications for future study designs. Consideration should be given to the duration and timing of observation or intervention study designs, by aiming to cover full temporal cycles where possible (e.g., record a 7-day period) and accounting for changes across seasons in statistical analyses. Whilst it is difficult to avoid this form of timing bias, this study and previous literature highlight general temporal trends for consideration. Exploring temporal patterns in daily movement behaviours over a yearly cycle in a large cohort is a new methodological paradigm made possible by advances in wearables. We are now able to measure these patterns with greater accuracy than ever before, and have the opportunity to understand the temporal context of changes, and potentially the health risks of different movement patterns.

Future research with larger and more geographically diverse samples would allow the impact of additional temporal events and other climates on daily movement patterns to be explored. Furthermore, exploration of intra-day variability in movement patterns across the year, and the relationship between any such variation and health outcomes may be valuable (e.g., the association between the timing of exercise and sleep, and flow on impacts on outcomes such as mental health). The seasonal differences observed in this study suggest weather variables are likely contributors to movement patterns and further exploration is warranted. Finally, the Christmas-New Year period appears to be an important time for short-term movement behaviour changes. It is however a time when many people take vacations. Studying the association between vacations and movement behaviours may highlight a potentially important context for intervention development.

4.6 Conclusion

The results of this study suggest that within-year fluctuations in sleep, sedentary behaviour and physical activity are associated with events such as the Christmas-New Year period and daylight saving time transitions, which are overlaid on weekly and seasonal rhythms. High fidelity measurement of daily activity patterns holds the potential to pinpoint periods of highest risk changes in behaviour, which may be addressed in time-targeting interventions.

4.7 Declarations

Acknowledgements

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Authors' contributions

TF participated in the design of the study, contributed to data collection, data processing and conducting statistical analyses. CM, RC and FF participated in the design of the study, contributed to data collection and data processing. All authors contributed to the statistical analysis plan and to writing the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

Chapter 5

Weather associations with physical activity, sedentary behaviour and sleep patterns of Australian adults: a longitudinal study with implications for climate change

This chapter presents the manuscript of a published cohort study, which has been formatted to match the style of the overall thesis. This chapter details the association of weather with the movement-related behaviours of the ARIA study participants. The aim of this study was to explore the associations between movement-related behaviours and weather variables, including maximum and minimum temperature, rainfall, wind speed, cloud cover and daily sunshine. The original article is included as Appendix 5.1.[163] A signed Statement of Authorship form for the relative contribution of all authors to this manuscript is in Appendix 5.2.

Citation:

Ferguson T, Curtis R, Fraysse F, Olds T, Dumuid D, Brown W, Esterman A, Maher C. Weather associations with physical activity, sedentary behaviour and sleep patterns of Australian adults: a longitudinal study with implications for climate change. International Journal of Behavioral Nutrition and Physical Activity. 2023;20(1):30.

5.1 Abstract

Background

Weather is a potentially important influence on how time is allocated to sleep, sedentary behaviour and physical activity across the 24-hour day. Extremes of weather (very hot, cold, windy or wet) can create undesirable, unsafe outdoor environments for exercise or active transport, impact the comfort of sleeping environments, and increase time indoors. This 13-month prospective cohort study explored associations between weather and 24-hour movement behaviour patterns.

Methods

368 adults from Adelaide, Australia, wore Fitbit Charge 3 activity trackers 24 hours a day for 13 months with minute-by-minute data on sleep, sedentary behaviour, light physical activity (LPA), and moderate-to-vigorous physical activity (MVPA) collected remotely. Daily weather data included temperature, rainfall, wind speed, cloud cover and sunshine. Multi-level mixed-effects linear regression analyses (one model per outcome) were used.

Results

90,801 days of data were analysed. Sleep was negatively associated with minimum temperature (-12 min/day, range = 31.2°C, p=0.001). Sedentary behaviour was positively associated with minimum temperature (+12 min/day, range = 31.2 °C, p=0.006) and wind speed (+10 min/day, range = 36.7 km/h, p<0.001), and negatively associated with sunshine (-17 min/day, range = 13.9 hr, p<0.001). LPA was positively associated with minimum temperature (+11 min/day, range = 31.2°C, p=0.002), cloud cover (+4 min/day, range = 8 eighths, p=0.008) and sunshine (+17 min/day, range = 13.9 hr, p<0.001), and negatively associated with wind speed (-8 min/day, range = 36.7 km/h, p<0.001). MVPA was positively associated with sunshine (+3 min/day, range = 13.9 hr, p<0.001) and negatively associated with minimum temperature (-13 min/day, range = 31.2 °C, p<0.001), rainfall (-3 min/day, range = 33.2 mm, p=0.006) and wind speed (-4min/day, range = 36.7 km/h, p<0.001). For maximum temperature, a significant (p<0.05) curvilinear association was observed with sleep (half-U curve) and physical activity (inverted-U curve), where the decrease in sleep duration appeared to slow around 23°C, LPA peaked at 31 °C and MVPA at 27°C.

Conclusion

Generally, adults tended to be less active and more sedentary during extremes of weather and sleep less as temperatures rise. These findings have the potential to inform the timing and content of positive movement behaviour messaging and interventions.

Trial registration

The study was prospectively registered on the Australian New Zealand Clinical Trial Registry (Trial ID: ACTRN12619001430123).

Keywords

Physical activity, sedentary behaviour, sleep, weather, movement behaviours, 24-hour day, time use, temperature, rainfall, wind speed

5.2 Introduction

At any time of the day, a person is engaged in one of three movement behaviours; sleeping, being sedentary, or being active.[141] The relative distribution of these behaviours has impacts on health. Insufficient physical activity or sleep, and excess sleep or sedentary behaviour are associated with poor health outcomes, including increased risk of chronic illness and reduced life expectancy.[34, 42, 79, 144] When considering day-to-day changes in movement behaviours, each is intrinsically linked, whereby changes in one behaviour result in equal and opposite changes across the remaining behaviours.[164] The time allocated to each behaviour in a 24-hour day is influenced by both internal factors such as motivation, fatigue, and physical health, and external factors, including work or family commitments, physical environment, resource availability and the weather.[146, 165, 166]

The weather we experience each day is the result of a complex and ever-changing system of atmospheric variables.[167] Weather conditions can either afford or limit opportunities to participate in movement behaviours. This may be directly, for example through impacting thermoregulation,[168] or indirectly by changing the usability and safety of the physical environment.[145] Whilst weather is not an acutely modifiable factor, understanding its association with movement behaviours is valuable for identifying potential conditions where less favourable movement behaviour patterns occur.

Extremes of weather (i.e. too hot, cold, windy or wet) reduces mobility and engagement with our physical environment.[145, 154] This may limit opportunities for physical activity, including outdoor exercise, recreation, and safe active transport, reduce the comfort of sleeping environments, and more time may be spent indoors where sedentary pursuits are common (i.e. sitting, watching TV, using computers and mobile devices).[155] Current literature suggests that in general adults sleep less as temperatures rise, are more sedentary when rainfall is higher or temperatures are lower, and are less active during extremes of temperature, and during higher rainfall and wind speeds.[153, 169-172] There is currently no clear association between movement behaviours and cloud cover or daily sunlight volume. The direction of the associations are more generalisable than specific magnitudes, as weather is regionally specific.[153] Weather patterns are influenced by a region's distance from the equator, daylight hours, height above sea level, topography and proximity to the ocean.[173]

There are several limitations to the current body of evidence for weather-based research. Broadly, a large portion of studies has focused on seasonal changes, which provides only a low-resolution comparison of weather conditions in specific timepoints across the year.[153] Additionally, studies have mostly used cross-sectional designs with subjectively measured movement behaviours, and often explore movement behaviours in isolation, e.g. physical activity only.[153] To our knowledge, no studies anywhere in the world have used a longitudinal design over a full 12-month seasonal cycle, to capture 24-hour movement behaviour. The current study aims to fill these gaps by exploring the associations between weather conditions (maximum temperature, minimum temperature, rainfall, wind speed, cloud cover and sunshine) and daily device-measured movement behaviours (sleep, sedentary behaviour, light physical activity and moderate-to-vigorous physical activity) and to comment on how these associations fit with climate change projections. The findings may assist with the timing and design of movement behaviour interventions.

5.3 Methods

5.3.1 Study design

Data collected from the *Annual Rhythms In Adults' lifestyle and health* (ARIA) prospective cohort study were used in this analysis. ARIA collected data on body weight, 24-hour movement behaviours, dietary patterns and wellbeing in a cohort of Australian adults over a 13-month period. Further details of the study protocol have been published elsewhere.[121]

Ethics approval was provided by the University of South Australia Human Research Ethics committee (Protocol number: 201901). The study was prospectively registered on the Australian New Zealand Clinical Trial Registry (Trial ID: ACTRN12619001430123).

5.3.2 Setting and participants

375 community-based adults were recruited from the greater metropolitan area of Adelaide, South Australia for the ARIA study. They were recruited in two ways: (1) parents of children enrolled in a separate cohort study called *Life on Holidays* [123] (cohorts 1 and 2), or (2) parents

of primary school children recruited from the community through general advertising (i.e. social media posts, paid digital advertisements, community notice boards) (cohort 3).

Enrolment occurred in two waves: cohort 1 participants commenced on 1st December 2019, cohorts 2 and 3 commenced on 1st December 2020. Each wave remained in the study until the end of the following December (31st December 2020 and 31st December 2021 respectively), totalling 13 months in the study.

Inclusion criteria were: age 18 to 65 years; a parent/guardian of a child enrolled in Life on Holidays study or a parent/guardian of child aged 5 to 12 years; residing in the greater metropolitan Adelaide area; having access to a Bluetooth-enabled mobile phone or computer and home internet; being proficient in English; and being ambulant. Exclusion criteria were: being pregnant; having an implanted electronic medical device; or receiving treatment for, or experiencing, any life-threatening condition which impacted daily lifestyle and health.

A researcher visited each eligible and consenting participant at their home between August and November in the year of commencing the study. At this visit baseline height was measured and participants completed a baseline survey containing demographic, health and lifestyle items. Participants were provided with a Fitbit Charge 3 fitness tracker and Fitbit Aria body weight scale (Aria 2 or Aria Air scale, Fitbit Inc., San Francisco, CA, USA).

During the study period, participants used the Fitbit devices daily and completed eight follow-up surveys of wellbeing and diet (not used in the current analysis). Participants did not require any face-to-face session after the baseline visit, unless technical support was required. On completion of the study, participants received an honorarium of $100 and were able to keep the Fitbit Charge 3 and Aria scale.

5.3.3 Variables

Daily movement behaviour patterns

Device-measured minute-by-minute movement behaviour data were collected using a wrist-worn Fitbit Charge 3 activity tracker (Fitbit Inc., San Francisco, CA, USA). The device was worn on the participants' non-dominant wrist, 24 hours a day (except whilst charging or during water activities). Participants were asked to sync data to the linked Fitbit user account

frequently (at least every 5 days), so that data could be collected remotely via purpose-built software called “Fitnesslink” (Portal Australia, Adelaide, Australia).

Each minute was classified as either sleep, sedentary behaviour, light physical activity, moderate or vigorous physical activity, or non-wear time, using Fitbit's proprietary algorithm. Fitbit devices have shown acceptable validity for sleep duration (compared to polysomnography: Charge 2 sensitivity = 0.96, specificity = 0.61;[125] Flex r = 0.97[126]), sedentary behaviour (compared to ActivPAL: Charge 3 ICC = 0.94 (95% CI: 0.92–0.96[127])) and moderate-to-vigorous physical activity (compared to Actigraph: Charge 2 ICC = 0.69 (95% CI: 0.35–0.87)[129], Flex r = 0.73[128]).

Weather

Adelaide is the capital city of South Australia with a population of approximately 1.4 million people. The metropolitan area is situated on a western coastline with flat plains extending toward steep hills in the eastern and southern regions (34° latitude and 138° longitude).[174] Adelaide's climate is considered temperate (Köppen classification),[118] and is characterised by four distinct seasons, including cold wet winters and warm dry summers.[175] Average weather data during the study are summarised in Table 5.1 and detailed descriptive weather summarises are found in Appendix 5.2. Daily weather data for Adelaide were collected from the Australian Data Archive for Meteorology.[176] Weather variables were reported as the average of data from five major weather stations spread geographically across the Adelaide metropolitan area. Maximum temperature (°C), minimum temperature (°C), rainfall (mm) and sunshine (defined as “bright” sunshine, which is less than visible sunshine) were reported as a single daily value. Wind speed (km/h) was reported as maximum gust, and at 9am and 3pm daily, with an average of the three values used to derive an overall daily value. Relative humidity (%) and cloud cover (eighths) were reported twice daily (9am and 3pm) with an average of the two used to derive an overall daily value. Average temperature (°C) was calculated as the mean of maximum and minimum temperatures. Apparent temperature (°C) was calculated using the Steadman formula[177] incorporating average temperature, humidity, wind speed and atmospheric pressure (hPa).

Table 5.1 - Average monthly weather during study period

	Summer			*Autumn*			*Winter*			*Spring*		
	Dec	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*
Daily min temp (°C)	14.3	15.6	15.0	13.8	11.5	9.2	7.7	6.6	7.4	9.5	10.2	12.9
Daily max temp (°C)	27.0	27.9	25.7	24.8	21.2	17.2	15.1	14.2	15.1	18.9	20.4	24.8
Total rainfall (mm)	11.0	27.9	34.1	11.1	58.4	50.6	99.8	65.9	55.3	53.2	62.1	29.5
Daily windspeed (km/h)	24.4	23.7	22.6	22.2	20.6	21.9	21.4	22.7	23.1	25.7	23.8	24.4
Daily sunshine (hr)	10.5	10.2	9.5	8.6	7.1	5.3	5.0	5.1	6.6	7.4	7.8	9.2
Daily cloud cover (/8)	3.4	3.6	3.8	4.1	4.3	5.4	5.4	5.3	4.6	4.6	4.7	4.5

Notes: Colour gradient represents lowest month (darkest blue) to highest month (darkest orange) for each variable. Each column is the average of the years over which the study was conducted, i.e. January to November columns are the average of 2020 and 2021, and December is the average of 2019, 2020 and 2021. Max = maximum, min = minimum, temp = temperature.

Demographic characteristics

At baseline, participants reported their sex, date of birth, marital status, number of children in household, highest education level, combined gross household income and hours of work per week outside the home.

5.3.4 Statistical analysis

Daily total minutes of sleep, sedentary behaviour, light physical activity and moderate-to-vigorous physical activity were calculated for each participant day. A valid day was defined as 18 hours or more of wear-time including a period of sleep. Moderate-to-vigorous physical activity was calculated as the sum of moderate physical activity and vigorous physical activity daily totals. Days on which a participant reported being away from home on vacation were excluded from analyses. Participants were included if they had at least 2 valid days of data.

Prior to performing the primary statistical analyses, independent weather variables were compared for collinearity (Table 2). Where a high correlation (≥0.80) was present, only one of the paired variables was included in the primary analyses. Specifically, maximum temperature was retained as it was the only common variable across all high correlation pairings. Six weather variables were retained from the original nine, these were minimum temperature, maximum temperature, rainfall, wind speed, sunshine and cloud cover.

Table 5.2 - Pearson correlation coefficients between weather variables

	Min temp	*Max temp*	*Avg temp*	*App temp*	*Rainfall*	*Sunshine*	*Humidity*	*Wind speed*	*Cloud cover*
Min temp									
Max temp	0.77								
Avg temp	**0.92**	**0.96**							
App temp	**0.90**	**0.93**	**0.97**						
Rainfall	-0.11	-0.31	-0.24	-0.24					
Sunshine	0.11	0.48	0.35	0.32	-0.22				
Humidity	-0.49	**-0.82**	-0.73	-0.61	0.39	-0.50			
Wind speed	0.22	-0.03	0.07	-0.11	0.22	-0.10	-0.04		
Cloud cover	-0.03	-0.38	-0.25	-0.23	0.20	-0.78	0.44	0.18	

Notes: Bold indicates a high correlation (≥±0.80). Avg = average, app = apparent, maximum, min = minimum, temp = temperature.

Independent vs dependent variable scatterplots of raw data were generated in R version 4.1.3 (R Foundation for Statistical Computing, Vienna, Austria) and presented as smoothing lines with 95% confidence intervals using generalised linear models for linear relationships and generalised additive models for quadratic relationships. A quadratic relationship was observed between maximum temperature and movement behaviour variables; to account for this relationship a variable of maximum temperature squared was included in the analyses.

Multi-level mixed-effects linear regression analyses were performed using Stata 17 (StataCorp, College Station, TX, USA) with statistical significance set at 0.05. Multilevel modelling with random intercepts was used to adjust for the non-independence of the data and to account for nesting of repeated measures within individuals, individuals within families, and families within waves. The movement behaviours were the dependent variables (one per model). The weather variables were included as fixed effects (all included in the same model). The regression coefficients for the weather variables were used to identify the difference in daily minutes of movement behaviours associated with an increase of one degree of temperature, one millimetre of rainfall, one kilometre per hour of wind speed, an eighth of cloud cover, and one minute of sunshine.

5.4 Results

5.4.1 Participants

Movement behaviour data were available for 368 of the initial 375 enrolled (see Table 5.3). Participants were predominantly mid-aged (mean = 40 years [SD = 6 years], range = 27 to 65 years), overweight or obese (34% and 35% respectively), married or in de facto relationships (85%), and had two or more children in their household (90%). Almost half the participants were educated to university level (48%), worked full time equivalent hours (46%), worked in managerial or professional occupations (40%) and had a household income between $100,000 and $200,000 (48%).

Table 5.3 - Participant demographics (N = 368)

	Mean	(SD)
Age (years)	40.2	(5.9)
Weight (kg)	84.0	(20.5)
Height (cm)	170.4	(9.5)
	n	**(%)**
Sex		
Female	209	(56.8)
Male	159	(43.2)
Weight status		
Underweight	1	(0.3)
Normal	114	(31.0)
Overweight	124	(33.7)
Obese	129	(35.1)
Smoker	34	(9.2)
Aboriginal and Torres Strait Islander peoples	4	(1.1)
Born in Australia	279	(75.8)
Marital status		
Never married	26	(7.1)
Married/de facto	313	(85.1)
Separated, divorced or widowed	29	(7.8)
Chronic illness		
None	163	(44.3)
Single	107	(29.1)
Multiple	98	(26.6)

Sleep chronotype		
Definitely a morning type	82	(22.3)
More a morning type than evening type	122	(33.2)
More an evening type than morning type	111	(30.2)
Definitely an evening type	53	(14.4)
Adults in household		
One	38	(10.3)
Two	305	(82.9)
Three	17	(4.6)
Four or more	7	(1.9)
Children in household		
One	36	(9.8)
Two	195	(53.0)
Three	95	(25.8)
Four or more	42	(11.5)
Education		
Year 10 or less	17	(4.6)
Year 11 - 12	49	(13.3)
Certificate/Diploma	125	(34.0)
University degree	177	(48.1)
Occupation		
Managerial and professional	148	(40.2)
Technical and clerical	77	(20.9)
Community, personal service, sales	67	(18.2)
Machinery operators, drivers, labourers	14	(3.8)
No job/other	62	(16.8)
Household income (Australian dollars)		
< $50,000	37	(10.1)
Between $50,000 and $99,999	111	(30.2)
Between $100,000 and $199,999	176	(47.8)
≥$200,000	44	(12.0)
Hours worked per week		
None	55	(14.9)
<15	25	(6.8)
15-35	119	(32.3)
36+	169	(45.9)

5.4.2 Movement behaviour data

Data from 90,801 valid days were analysed, with an average of 247 (SD = 113) valid days per participant. On a day-by-day basis, the average percentage of participants with valid data was

64% (SD = 6.6%) with the daily percentage declining gradually over the 13-month study period (first month = 73%, thirteenth month = 51%). Across all valid days, participants' daily averages for movement behaviours were 8 hours and 10 minutes of sleep (SD = 89 minutes), 10 hours and 19 minutes of sedentary behaviour (SD = 120 minutes), 4 hours and 59 minutes of light physical activity (SD = 93 minutes) and 32 minutes of moderate-to-vigorous physical activity (SD = 38 minutes).

5.4.3 Associations between weather and movement behaviours

The relationships between temperature (maximum and minimum) and observed raw movement behaviour data are shown in Figure 5.1. For maximum temperature, the non-linear relationship is represented using generalised additive models for line fitting. Notably, both light physical activity and moderate-to-vigorous physical activity increase with temperature from 9 °C towards a peak at approximately 31 °C and 27 °C respectively, before decreasing as temperature increases to the upper limit of 44 °C. The optimal 10 °C range for maximum temperature appears to be 25-35 °C for light physical activity and 22-32 °C for moderate-to-vigorous physical activity, giving an overlap of 25-32 °C for both activity types to be optimised.

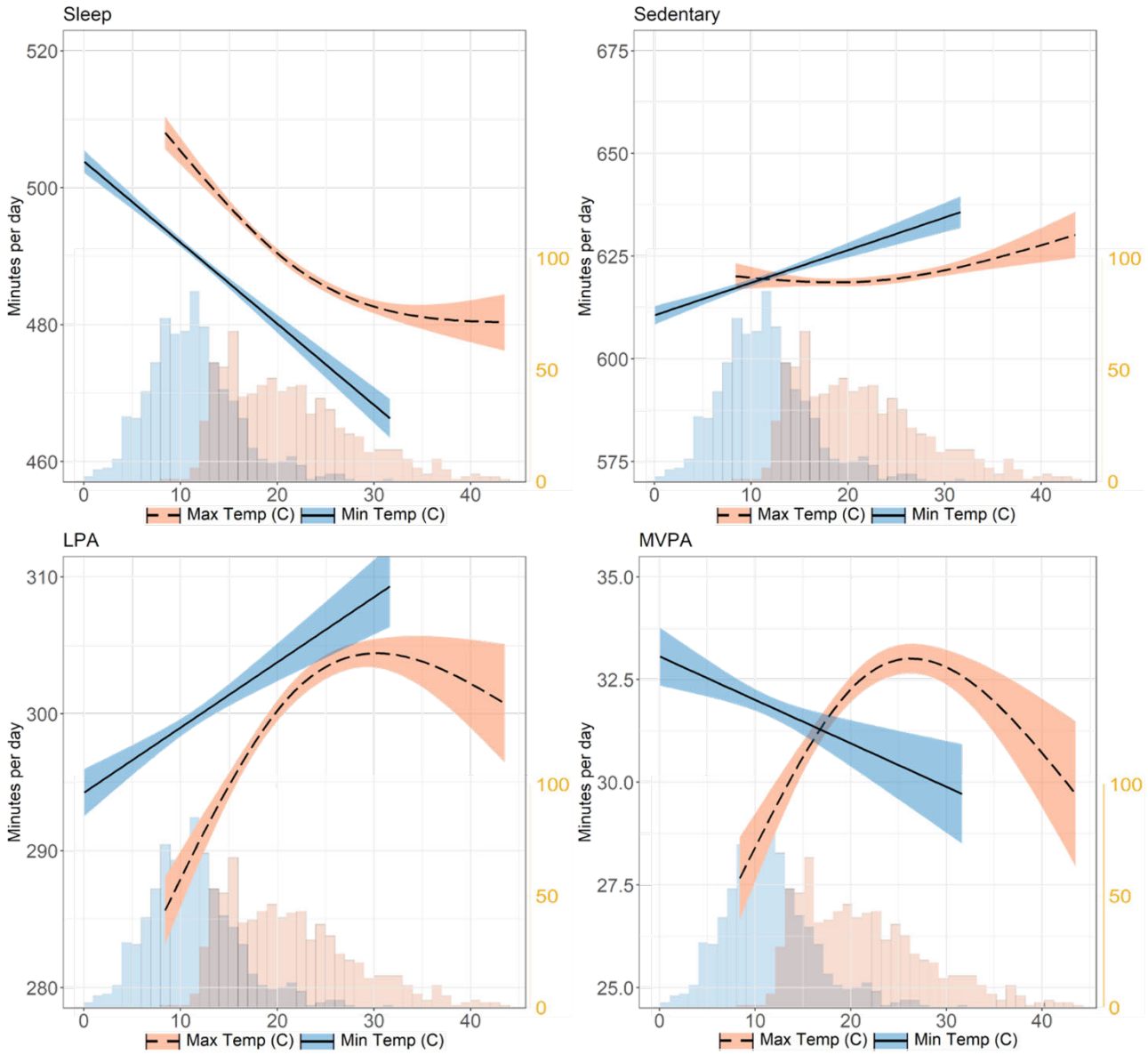


Figure 5.1 - Fitted line plot of daily maximum and minimum temperatures vs movement behaviours

Notes: Max Temp = maximum daily temperature (°C), Min Temp = minimum daily temperature (°C). Coloured area represents 95% confidence intervals. Generalised additive models used to produce Max Temp smoothed line and generalised linear models used to produce Min Temp smoothed line. Right y-axis represents histogram showing frequency of temperature at 1°C intervals for maximum daily temperature (blue) and minimum daily temperature (orange).

Results of multi-level mixed-effects linear regression analyses are presented in Table 5.4. Sleep, light physical activity and moderate-to-vigorous physical activity were all associated with both maximum temperature and maximum temperature squared, suggesting a curvilinear relationship. Sleep was also negatively associated with minimum temperature (-12 min/day,

range = 31.2°C). Sedentary behaviour was positively associated with minimum temperature and wind speed (+12 min/day, range = 31.2°C and +10 min/day, range = 36.7 km/h respectively), and negatively associated with sunshine (-17 min/day, range = 13.9 hr). Light physical activity was positively associated with minimum temperature (+11 min/day, range = 31.2 °C), cloud cover (+4 min/day, range = 8 eighths) and sunshine (+17 min/day, range = 13.9 hr), and negatively associated with wind speed (-8 min/day, range = 36.7 km/h). Moderate-to-vigorous physical activity was positively associated with sunshine (+3 min/day, range = 13.9 hr), and negatively associated with minimum temperature (-13 min/day, range = 31.2 °C), rainfall (-3 min/day, range = 33.2 mm), and wind speed (-4min/day, range = 36.7 km/h).

Table 5.4 - Associations between movement behaviours and weather

	Units	Coefficient	[95% CI]	p
Sleep *(model 1)*	*min*	*528*	*[520, 537]*	
Max temp	°C	**-2.31**	**[-2.88, -1.75]**	**<0.001**
Max temp^2	°C	**0.03**	**[0.02, 0.04]**	**<0.001**
Min temp	°C	**-0.37**	**[-0.59, -0.14]**	**0.001**
Rainfall	mm	0.04	[-0.11, 0.20]	0.564
Wind speed	km/h	0.47	[-0.04, 0.13]	0.264
Cloud cover	eighths	-0.26	[-0.62, 0.11]	0.168
Sunshine	min	-0.001	[-0.004, 0.003]	0.668
Sedentary *(model 2)*	*min*	*610*	*[592, 628]*	
Max temp	°C	-0.03	[-0.74, 0.68]	0.932
Max temp^2	°C	0.01	[-0.01, 0.02]	0.263
Min temp	°C	**0.39**	**[0.11, 0.68]**	**0.006**
Rainfall	mm	0.14	[-0.05, 0.33]	0.139
Wind speed	km/h	**0.26**	**[0.16, 0.36]**	**<0.001**
Cloud cover	eighths	-0.35	[-0.80, 0.11]	0.137
Sunshine	min	**-0.02**	**[-0.03, -0.02]**	**<0.001**
LPA *(model 3)*	*min*	*277*	*[263, 291]*	
Max temp	°C	**1.53**	**[1.02, 2.03]**	**<0.001**
Max temp^2	°C	**-0.03**	**[-0.04, -0.02]**	**<0.001**
Min temp	°C	**0.36**	**[0.16, 0.57]**	**0.002**
Rainfall	mm	-0.06	[-0.20, 0.07]	0.353
Wind speed	km/h	**-0.22**	**[-0.29, -0.15]**	**<0.001**
Cloud cover	eighths	**0.44**	**[0.11, 0.76]**	**0.008**
Sunshine	min	**0.02**	**[0.016, 0.024]**	**<0.001**

***MVPA** (model 4)*	*min*	*26*	*[22, 29]*	
Max temp	°C	**0.87**	**[0.64, 1.11]**	**<0.001**
Max temp^2	°C	**-0.01**	**[-0.02, -0.01]**	**<0.001**
Min temp	°C	**-0.41**	**[-0.51, -0.32]**	**<0.001**
Rainfall	mm	**-0.09**	**[-0.15, -0.03]**	**0.006**
Wind speed	km/h	**-0.10**	**[-0.13, -0.06]**	**<0.001**
Cloud cover	eighths	0.12	[-0.04, 0.27]	0.135
Sunshine	min	**0.003**	**[0.002, 0.005]**	**<0.001**

Notes: Results of multi-level mixed-effects linear regression analyses (one model per movement behaviour). Models adjusted for nesting of observations within participants, within families, within study waves. Bold and green shading indicates $p < 0.05$. LPA = light physical activity, max temp = maximum temperature, max temp^2 = maximum temperature squared, min temp = minimum temperature, MVPA = moderate-to-vigorous physical activity.

5.5 Discussion

This study explored the associations between daily weather conditions and device-measured movement behaviours using longitudinal data across a 13-month period. Several significant associations were observed. Sleep was inversely associated with minimum temperature, sedentary behaviour was inversely associated with sunshine, and positively associated with minimum temperature and windspeed. Light physical activity was inversely associated with windspeed, and positively associated with minimum temperature, cloud cover and sunshine. Moderate-to-vigorous physical activity was inversely associated with minimum temperature, rainfall, and windspeed, and positively associated with sunshine. For maximum temperature associations, an inverted-U curvilinear relationship was observed with both light and moderate-to-vigorous physical activity, and an exponential decay relationship with sleep (i.e. decreasing slope as maximum temperature increases). The directions of the associations observed in this study were largely consistent with previous literature.

5.5.1 Sleep

Sleep duration decreased as minimum temperature increased with an estimated reduction of 12 minutes across the 30 °C temperature range experienced by participants. This magnitude of change is consistent with a large global study in which a 9 minute reduction was observed over the same temperature range.[169] Additionally, comparable reductions in sleep were

observed in studies using self-reported sleep measures.[178] Participants in this study were, on average, within recommended sleep durations of 7 to 9 hours,[179] and the modelled range of sleep duration change would not have moved the average person outside these recommendations. However, it is important to consider that nightly sleep needs are person- and context-specific. Finally, the acute effect of accumulated sleep reduction over days or weeks of very high overnight temperatures are wide ranging, including reduced cognitive ability, increased stress responsivity, emotional distress and reduced well-being.[180] The ability to maintain favourable indoor temperatures is highly resource-dependent and the effect of high overnight temperatures is likely to be greater for poor and low-resourced populations.[181]

5.5.2 Physical activity

Light physical activity increased with minimum temperature, cloud cover and sunshine, and decreased as wind speed increased. These results are similar to the limited strength evidence in Turrisi et al.'s[153] review. No evidence was found for associations with cloud cover and sunshine in that review. Moderate-to-vigorous physical activity decreased as minimum temperature, rain and wind increased, and increased as sunshine increased. Combining this with the curvilinear relationship of maximum temperature, it appears ideal conditions were dry, calm, sunny days where maximum temperatures ranged from 22°C-32 °C. Turrisi et al.[153] reported similar results, with strong evidence for a curvilinear relationship with maximum temperature. Interestingly, the percentage of days where minimum recommended physical activity levels were achieved was relatively stable across the 20-40 °C maximum temperature range (51.9%-53.5% range across 5 °C groupings). However, there was a sharp decrease in the number of days when physical activity guidelines were met, when the maximum temperature was above 40 °C (44.9% vs 52.3% for days 35-40 °C). At the population level, this is a meaningful decline in moderate-to-vigorous physical activity on very hot days.

When considering the physical environment, extremes of weather have the potential to create unsafe environments for exercise, active transport and simply being outdoors.[145] Rain reduces the quality of surfaces and visibility, wind reduces stability and increases surface debris, radiant heat can raise temperatures of asphalt, concrete and metal surfaces to unsafe levels.[145] It is easier to protect oneself from the elements with clothing and equipment (i.e. umbrella), or by staying indoors when being lightly active (i.e. walking), however this becomes more challenging with more demanding forms of activity such as cycling or running without

access to indoor exercise equipment. Risk of injury also increases with more vigorous activities in less controlled environments.

5.5.3 Sedentary behaviour

The duration of sedentary behaviour increased as wind and minimum temperature increased, and decreased when sunshine increased. These findings are consistent with the moderate strength evidence reported by Turissi et al.[153] for temperature, and the limited strength evidence for windspeed.[153] No association between sedentary behaviour and rainfall or cloud cover is also consistent with Turissi et al.'s findings.[153] Interestingly, when looking at significant pairings of movement behaviours, seven involved sedentary behaviour and another movement behaviour, five of which were opposite association pairings. This suggests time allocation more commonly swaps between sedentary behaviour and the other movement behaviours. This swapping is supported by perceptions of extremes of weather as a barrier to physical activity, a negative correlate of sleep, and a positive correlate of sedentary behaviour.[182-184]

5.5.4 Strengths and limitations

To our knowledge, this is the first longitudinal study of one year duration that captures 24-hour movement behaviours in an adult population. The dataset included device-measured movement behaviour and climatic data. This is a large, high-quality dataset for answering the research questions at hand. There are a few limitations to consider. The sample size limited the study's power to explore potential participant sub-group differences. Data were collected in a single Australian city with a Mediterranean climate.[118] Thus, the findings are likely to be most applicable to other temperate climate regions (which includes parts of North and South America, Africa and Europe), and do not provide insight into extreme climates such as extremely cold or tropical climates. The population consisted of adults with primary-school-aged children, so adults' weather-related behaviour may additionally reflect the needs of children in their care. Furthermore, data collection took place from 2019-2021, much of which was within the COVID-19 pandemic period. Due to Australia's strict quarantine approach, lifestyles of individuals residing in Adelaide were not harshly impacted by COVID-19, though there were periods in which working from home for non-essential workers was encouraged, and short periods of gym closures (less than one week durations, after an initial two-month shutdown).

5.5.5 Implications for intervention design

Several implications for intervention and health promotion campaigns should be considered. Firstly, the weather may influence intervention effects. For example, if an intervention spans months or seasons with meaningfully different weather conditions, weather should be considered when discussing findings, or potentially be included in statistical analyses. At the person-specific level, an interesting opportunity exists to explore a strategy known as just-in-time adaptive interventions. These are study designs that adapt the amount of intervention to the individual's context.[185] By leveraging longitudinal activity tracker data and combining this with weather forecasting, an opportunity exists to tailor health promotion messaging or intervention content to the individual at the specific time it is most needed. Future research in this area is warranted. Finally, community-level health promotion campaigns may be timed to target periods in the year, either by season or month, where less favourable weather conditions historically occur, i.e. promoting sleep and sleep hygiene in summer months, or ideas for "swapping" outdoor physical activity for indoor alternatives in winter and inclement weather.

5.5.6 Implications in the context of climate change

At present, we are amid an unprecedented climate crisis.[186] Global temperatures are increasing, rainfall patterns are changing, and the frequency of extreme weather events is on the rise.[186] This is having far-reaching negative health consequences.[181, 187-189] As these patterns progress, the number of days each year where weather conditions are favourable for movement behaviours and outdoor environments are accessible for recreation is likely to decrease.

There are several options for mitigating the negative health effects of a changing climate, at both the individual level and as a society. Individually, a push toward increasing active transport has health and financial benefits to the individual, whilst also reducing a person's CO_2 emissions and contribution to traffic congestion.[190] Whilst this is a viable option, a caveat is that this type of activity is highly weather dependent, and viability is likely to decrease as climate change progresses. Another approach is extremes of weather action planning. Provision of freely accessible sheltered and indoor recreation areas is needed, especially in more extreme climate locations and for low-resourced populations.[191]

5.6 Conclusion

The results suggest modest significant associations between a range of weather variables and movement behaviours. In general, participants tended to be less active and more sedentary during extremes of weather and slept less as temperatures increased These findings have the potential to inform the timing and content of health promotion interventions at both the community and individual level, along with suggesting how health-related behaviours may be impacted over the coming decades by climate change.

5.7 Declarations

Ethics approval and consent to participate

Ethics approval was provided by the University of South Australia Human Research Ethics committee (UniSA HREC, Protocol number: 201901) and participants provided written, informed consent prior to commencing participation.

Availability of data and materials

Data used in the current study are available and may be obtained from the corresponding author upon reasonable request.

Competing interests

The authors report no conflict of interest

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Authors' contributions

TF, CM, RC and FF were responsible for study inception and design. TF consolidated and cleaned data for analysis. All authors contributed to the statistical analysis plan with TF conducting the analyses. TF led manuscript writing and all authors conducted a critical revision and provided substantive feedback on the manuscript, in addition to approval of the final version.

Acknowledgements

Not applicable

Chapter 6

How do 24-hour movement behaviours change during and after vacation? A cohort study

This chapter presents the manuscript of a published cohort study, which has been formatted to match the style of the overall thesis. This chapter details the association of vacations with changes in movement-related behaviours of ARIA study participants. The aim of this study was to explore the associations between vacations and movement-related behaviours by comparing pre-vacation movement patterns to during and after vacations. The original article is included as Appendix 6.1.[192] A signed Statement of Authorship form for the relative contribution of all authors to this manuscript is in Appendix 6.2.

Citation:
Ferguson T, Curtis R, Fraysse F, Olds T, Dumuid D, Brown W, Esterman A, Maher C. How do 24-hour movement behaviours change during and after vacation? A cohort study. International Journal of Behavioral Nutrition and Physical Activity. 2022; 2023;20(1):24.

6.1 Abstract

Background

For adults, vacations represent a break from daily responsibilities of work – offering the opportunity to re-distribute time between sleep, sedentary behaviour, light physical activity (LPA) and moderate-to-vigorous physical activity (MVPA) across the 24-hour day. To date, there has been minimal research into how activity behaviour patterns change on vacation, and whether any changes linger after the vacation. This study examined how daily movement behaviours change from before, to during and after vacations, and whether these varied based on the type of vacation and vacation duration.

Methods

Data collected during the Annual Rhythms In Adults' lifestyle and health (ARIA) study were used. 308 adults (mean age 40.4 years, SD 5.6) wore Fitbit Charge 3 fitness trackers 24 hours a day for 13 months. Minute-by-minute movement behaviour data were aggregated into daily totals. Multi-level mixed-effects linear regressions were used to compare movement behaviours during and post-vacation (4 weeks) to pre-vacation levels (14 days), and to examine the associations with vacation type and duration.

Results

Participants took an average of 2.6 (SD=1.7) vacations of 12 (SD=14) days' (N=9778 days) duration. The most common vacation type was outdoor recreation (35%) followed by family/social events (31%), rest (17%) and non-leisure (17%).

Daily sleep, LPA and MVPA all increased (+21 min [95% CI=19,24] $p<0.001$, +3 min [95% CI=0.4,5] $p<0.02$, and +5 min [95% CI=3,6] $p<0.001$ respectively) and sedentary behaviour decreased (-29 min [95% CI=-32,-25] $p<0.001$) during vacation. Post-vacation, sleep remained elevated for two weeks; MVPA returned to pre-vacation levels; and LPA and sedentary behaviour over-corrected, with LPA significantly lower for 4 weeks, and sedentary behaviour significantly higher for one week. The largest changes were seen for "rest" and "outdoor" vacations. The magnitude of changes was smallest for short vacations (<3 days).

Conclusion

Vacations are associated with favourable changes in daily movement behaviours. These data provide preliminary evidence of the health benefits of vacations.

Trial registration

The study was prospectively registered on the Australian New Zealand Clinical Trial Registry (Trial ID: ACTRN12619001430123).

Keywords

Physical activity, sedentary behaviour, sleep, vacation, holiday, movement behaviours, 24-hour day, time use

6.2 Background

The demands of paid and unpaid work substantially reduce a person's ability to freely allocate their time. A standard workday accounts for approximately half an adult's waking hours.[193, 194] Additional time may need to be allocated to pre- and post-work related tasks (i.e. dressing, packing meals), along with commuting between home and the workplace. The average daily commute for workers globally is around an hour. [195-197] Further time allocation is needed for essential non-work tasks such as performing domestic duties, caring for loved ones, and attending appointments. Lastly, time must be given to self-care and sleep needs. After accounting for all these daily tasks, little is left to be allocated freely to such things as leisure pursuits, exercise, or rest.

When considering movement behaviours, throughout any day a person's activities may be considered on a movement continuum where they move between three broad behaviours of sleep, sedentary behaviour, and physical activity.[141] Further, a change in the time spent in one behaviour during a 24-hour period necessitates an equal and opposite change across the remaining behaviours.[140] A person's occupation largely dictates what movement behaviour a person can engage in (e.g. desk-based occupations generally require long periods of sedentary time, while labour-intense occupations require long periods of physical activity). How a person commutes to employment also has an influence on movement behaviours; for example, passive transport (such as public transport) is typically sedentary, whereas active transport (i.e. walking or cycling) requires a degree of physical activity. Finally, the volume and timing of work and essential non-work tasks primarily restrict the window available for sleep, and limits the opportunity for leisure-time sedentary behaviour and physical activity.

Vacations are an extended and relatively uninterrupted break from the usual demands on a person's time, offering greater freedom in time allocation. Across a calendar year, a person is likely to take several vacations for multiple different purposes.[198] The purpose of vacations varies widely and is specific to the needs of the individual, their income and household demographics.[198] A vacation may occur at home or away, be primarily for leisure (e.g. attending events, visiting attractions), social (visiting family or friends), or active (e.g. hiking, bushwalking) pursuits, for rest and relaxation, or for non-leisure tasks (i.e. caring for others, home renovations).

Health-focused vacation research has largely been directed towards physical and mental health and well-being changes associated with taking vacations. Broadly, vacations are associated with positive changes in self-reported health and well-being.[199-201] Conversely, vacations are also associated with less desirable changes such as overconsumption of food.[202] Less is known about the associations between vacations and movement behaviours. It is generally understood that too little or too much sleep, too little physical activity, and too much sedentary behaviour are associated with poorer health, increased risk of chronic illness, and increased mortality.[42, 79, 144, 203] Understanding the association between vacations and movement behaviours offers potential for targeted and timely interventions to improve or maintain favourable levels of each behaviour.

To our knowledge, just two studies have explored adults' movement behaviours during vacations. De Bloom et al [204] recruited paid workers in The Netherlands (n = 54) who went on vacations of longer than two weeks. Participants self-reported 7.4 hours of sleep during vacation compared to 6.7 hours pre-vacation. Cooper et al [205] explored self-reported physical activity and sedentary behaviour levels before, during and after vacation in US adults (n=122). They found a non-significant trend towards an increase in total physical activity during vacation compared to pre-vacation and a significant decrease 6-weeks post-vacation compared to during vacation. Moderate physical activity was significantly lower on vacation compared to pre- and post-vacation whilst vigorous physical activity did not change across time points.[205] In this same study, additional unpublished data were obtained from the authors which showed a non-significant trend towards less sedentary behaviour during vacation compared to pre- and post-vacation.[71, 205]

At present, no studies have used objective measures to explore changes in movement behaviours across the 24-hour day during vacations. This study aims to address this gap by:

- Describing the characteristics of vacations across a 13-month period (number, duration, timing, key activities)
- Examining how objectively measured daily movement behaviours change from before, to during, and post-vacation periods, and how these vary depending on the type of vacation and vacation duration.

- Identifying the sociodemographic and occupation characteristics associated with favourable changes in movement behaviours during and after vacations.

6.3 Methods

6.3.1 Study design

This study used data from the *Annual Rhythms In Adults' lifestyle and health* (ARIA) prospective cohort study which collected daily 24-hour movement behaviours in a cohort of Australian adults over a 13-month period. Full details of the study protocol have been previously published.[121]

6.3.2 Setting and procedure

ARIA included a community-based convenience sample of 375 adults, aged 18 to 65 years, recruited from the greater metropolitan area of Adelaide, South Australia.

Participants attended a face-to-face home visit, at which baseline measures (height, weight, and a demographic, health, and lifestyle characteristics survey) were collected and participants were provided with a Fitbit Charge 3 fitness tracker and Fitbit Aria body weight scale (Aria 2 or Aria Air scale; Fitbit Inc., San Francisco, CA, USA). Enrolment in the study occurred in two waves, with wave 1 data collection commencing on 1st Dec 2019 and concluding on 31st Dec 2020, and wave 2 data collection commencing on 1st Dec 2020 and concluding on 31st Dec 2021.

During the study, participants used the Fitbit devices daily and completed eight follow-up surveys which were spread throughout the 13-months, specifically December of the first calendar year, then January, March, April, June, August, October, and December of the second calendar year. These surveys comprised items relating to recreational physical activity, dietary intake, psychological wellbeing, weight perception/management, and work/holiday status. No further face-to-face sessions were needed unless for technical support. Upon completion of the study, participants received an honorarium of $100 and could keep their Fitbit Charge 3 and body weight scale if they wished.

6.3.3 Participants

Participants were recruited in two ways; either, they were parents of children enrolled in a separate cohort study, call Life on Holidays, [123] or they were adults recruited from the general public who had primary (i.e. elementary) school-aged children. Participants from the general public were recruited via advertising in digital media (i.e. Facebook posts and paid advertisements) and print media.

Inclusion criteria were being 18 to 65 years old, being a parent/guardian of a child enrolled in Life on Holidays study or a parent/guardian of a child aged 5 to 12 years, residing in greater metropolitan Adelaide, having access to a Bluetooth-enabled mobile device or computer and home internet, able to understand English, and being ambulant. Exclusion criteria were pregnancy, having an implanted electronic medical device, or experiencing or receiving treatment for any life-threatening condition which impacted daily lifestyle and health.

6.3.4 Variables

Movement behaviours

Objectively measured physical activity, sedentary behaviour and sleep were collected using a wrist-worn Fitbit Charge 3 activity tracker (Fitbit Inc., San Francisco, USA). Participants wore the device on their non-dominant wrist, 24 hours a day (except during showering, water-based activities or whilst charging the device) and were asked to sync data to their Fitbit user account at least every 5 days. Data were collected remotely via Fitnesslink software (Portal Australia, Adelaide, Australia), purpose-built for the ARIA study. Minute-by-minute activity data were recorded as sleep, sedentary behaviour, light physical activity, moderate physical activity, vigorous physical activity or non-wear according to Fitbit's proprietary algorithm. Previous models of Fitbit devices have demonstrated acceptable validity for moderate-to-vigorous physical activity (Flex compared to Actigraph GT3X+ r = 0.73 [128]), sleep (compared to polysomnography: Charge 2 sensitivity = 0.96, specificity = 0.61;[125] Flex r = 0.97[126]), sedentary time (compared to activPAL: ICC = 0.94, 95% CI: 0.92–0.96 [206]) and total daily energy expenditure (compared to doubly labelled water in free-living conditions: Flex r_s = 0.84[207]).

Vacation

As part of each follow-up survey, participants reported any dates they had been on vacation since the last survey, if they went away from home on any of those vacation dates. Participants were asked to describe the main purpose of the vacation in an open-ended item. Main purpose responses were grouped into four categories: 1) *Family or social events* (e.g. visiting family, friends, attractions, or attending entertainment events, observing religious or cultural periods (e.g. Christmas, Easter), 2) *Rest and relaxation,* 3) *Outdoor recreation* (e.g. hiking, sports, fishing, boating, camping) or 4) *Non-leisure* (e.g. caring for others, household jobs, medical leave).

Employment status

At baseline, participants reported their occupation, whether they worked shift work, and whether they regularly worked on weekends. During each follow-up survey, participants reported their average hours of worked per week, categorised as either no hours, <15 hours, 15-35 hours, or ≥36 hours.

Demographics

At baseline, participants' demographic and health data were collected, including sex, date of birth, marital status, number of children in household, highest education level (below year 10, year 11, year 12 or equivalent, certificate III/IV, advanced diploma/diploma, bachelor's degree, postgraduate or higher degree), combined gross household income (AUD <$50,000; $50,000-$99,999; $100,000-$199,999; ≥$200,000) and presence of chronic conditions.

Baseline anthropometry

At the baseline home visit, a research assistant measured height (Leicester Height Measure MKII, Invicta Plastics Ltd, Leicester, England) and weight (Fitbit Aria smart scales, Fitbit Inc., San Francisco, USA).

6.3.5 Statistical analysis

Daily minute totals were calculated for sleep, sedentary behaviour, light physical activity and moderate-to-vigorous physical activity. For a day to be valid, a total of at least 18 hours of data and a sleep period was required. Participants were included if they reported at least one vacation and had valid days of movement behaviour data pre-, during, and post-vacation.

For each vacation, mean daily sleep, sedentary, light physical activity, and moderate-to-vigorous physical activity time was calculated for the pre-vacation, during vacation, and post-vacation periods. Pre-vacation was defined as the fourteen days immediately prior to the vacation, excluding any vacation days from a previous vacation. Post-vacation was defined as the 28 days immediately after the vacation, considered in seven-day blocks (i.e. first, second, third and fourth week post-vacation), excluding any vacation days from a subsequent vacation.

All vacation and post-vacation periods were compared to pre-vacation periods for each movement behaviour using multi-level mixed-effects linear regression analyses. Analyses were completed in Stata 17 (StataCorp, College Station, TX, USA) with statistical significance set at 0.05. Random intercepts were used to account for the nested structure of the data (i.e. repeated measures within individuals, individuals within families, and families within waves). Movement behaviours were the dependent variables and were analysed in separate models. The vacation period (i.e. pre-, during or post vacation) was included as a fixed effect. The regression coefficients for vacation were used to identify the difference in daily minutes of movement behaviours during and post-vacation as relative to pre-vacation.

Additional sub-group analyses were completed for type of vacation (i.e., social, rest, outdoor recreation, non-leisure) and length of vacation (i.e., 3 days or less, 4-7 days, 8-14 days, over 14 days) using the same statistical approach as for overall vacation comparisons with each sub-group category analysed in separate models.

Interaction effects of participants' sociodemographic and occupation characteristics on movement behaviours during vacation were tested using multi-level mixed-effects linear regression (one model per movement behaviour, all sociodemographic and occupational characteristics included in each model). For these models only, Bonferroni corrections (p-value multiplied by total variables in the individual model) were used to adjust for the volume of comparisons.

6.4 Results

6.4.1 Participants

Of the 375 participants recruited, 308 went on at least one vacation where movement behaviour data were available. Participants were predominantly middle-aged (mean age 40.4 years, SD 5.6), overweight or obese, cohabitated, had 2-3 children at home, and were well-educated. Participants who reported paid employment were mostly day-workers (i.e. no shifts or weekends) and performed at least 15 hours of work per week (see Table 6.1). This sample was similar to middle-aged Australian adults in terms of BMI (69% overweight or obese vs 66% of 35- to 44-year-old Australian adults [208]), sex (55.2% women vs 50.8% of 35- to 44-year-old Australian adults [209]) and smoking status (8.4% vs 11.7% of 35- to 44-year-old Australian adults [210]). However, there were slightly more people born in Australia (78.2% vs 67% of 30- to 49-year-old Australian adults [211]), in a domestic relationship (87.7% married or defacto vs 74% of 34- to 44-year-old Australian adults [211]), parents (100% were parents whereas 77% of Australian women aged 30 to 49 years report having children [211]), and employed persons (88.4% reported working vs 75% of 35- to 45-year-old Australian adults [211]). The sample had slightly higher rates of non-school education (83.4% with a non-school qualification vs approximately 75% of 30- to 50-year-old Australian adults[212]).

Table 6.1 - Participant and vacation characteristics (N =308)

	n	(%)	Mean (SD)
Participant characteristics			
Age			40.4 (5.6)
Weight (kg)			83.7 (21.2)
Height (cm)			170.6 (9.6)
Female	170	(55.2)	
Male	138	(44.8)	
Body Mass Index (kg/m^2)			
Underweight	1	(0.3)	
Normal	94	(30.5)	
Overweight	104	(33.8)	
Obese	109	(35.4)	
Smoker	26	(8.4)	
Born in Australia	241	(78.2)	
Aboriginal and Torres Strait Islander peoples	2	(0.6)	
Marital status			
Never married	15	(4.9)	
Married/de facto	270	(87.7)	
Separated, divorced or widowed	23	(7.5)	
Chronic illness			
None	140	(45.5)	
Single	88	(28.6)	
Multiple	80	(26.0)	
Adults in household			
One	28	(9.1)	
Two	264	(85.7)	
Three	12	(3.9)	
Four or more	4	(1.3)	
Children in household			
One	27	(8.8)	
Two	171	(55.5)	
Three	79	(25.7)	
Four or more	31	(10.1)	
Education			
Year 10 or less	15	(4.9)	
Year 11 - 12	36	(11.7)	
Certificate/Diploma	107	(34.7)	
University degree	150	(48.7)	
Occupation			
Managerial and professional	135	(43.8)	
Technical and clerical	70	(22.7)	

Community, personal service and sales	56	(18.2)		
Machinery operators, drivers, and labourers	12	(3.9)		
No job/other	35	(11.4)		
Income (Australian dollars)				
< $50,000	22	(7.1)		
Between $50,000 and $99,999	93	(30.2)		
Between $100,000 and $199,999	151	(49.0)		
≥$200,000	42	(13.6)		
Hours worked per week				
None	31	(10.1)		
<15	20	(6.5)		
15-35	107	(34.7)		
36+	150	(48.7)		
Typical work pattern				
Weekdays only, no shift	214	(69.5)		
Weekdays and weekends	35	(11.4)		
Weekdays and shifts (inc. nights)	6	(1.9)		
Weekdays, weekends and shifts (inc. nights)	33	(10.7)		
Not applicable	20	(6.5)		
Vacation characteristics				
Total vacations	806			
Total vacation days	9778			
Vacations per participant			2.6	1.7
Vacation duration (days)			12.1	14.1
Vacation type (days)				
Outdoor recreation	2140	35.2		
Family or social events	3140	30.6		
Rest and relaxation	1618	17.1		
Non-leisure activities	2892	16.6		

6.4.2 Vacation characteristics

A total of 806 vacations were reported. Participants, on average, took less than three vacations per year (mean = 2.6, SD = 1.7) for a duration of 12 days on each occasion (mean = 12.1 days, SD = 14.1 days). The most common vacation purpose reported was *outdoor recreation* (35.2%), followed by *family or social events* (30.6%), *rest and relaxation* (17.1%) and *non-leisure activities* (16.6%). The distribution of vacations across the study period is shown in Figure 6.1, showing that participants tended to take vacations more frequently during the Christmas and New Year period (>50% of participants per day), school holidays, and on public holidays. Activity tracker non-wear time was consistent across the vacation

period, with daily averages of 3.8% for pre-vacation, 3.9% during vacation and 3.7% post vacation. Compared to pre-vacation weekdays and weekends, movement behaviours during vacation appear closer to weekend patterns than weekday (Appendix 6.3). Vacation days closely resembled weekend days, with mean differences between vacations and non-vacation weekends ranging from –3.0% for sedentary behaviour to +2.7% for sleep. By contrast, mean differences between non-vacation weekdays and vacations were very wide, ranging from –14.8% for MVPA to +8.1% for sedentary behaviour.

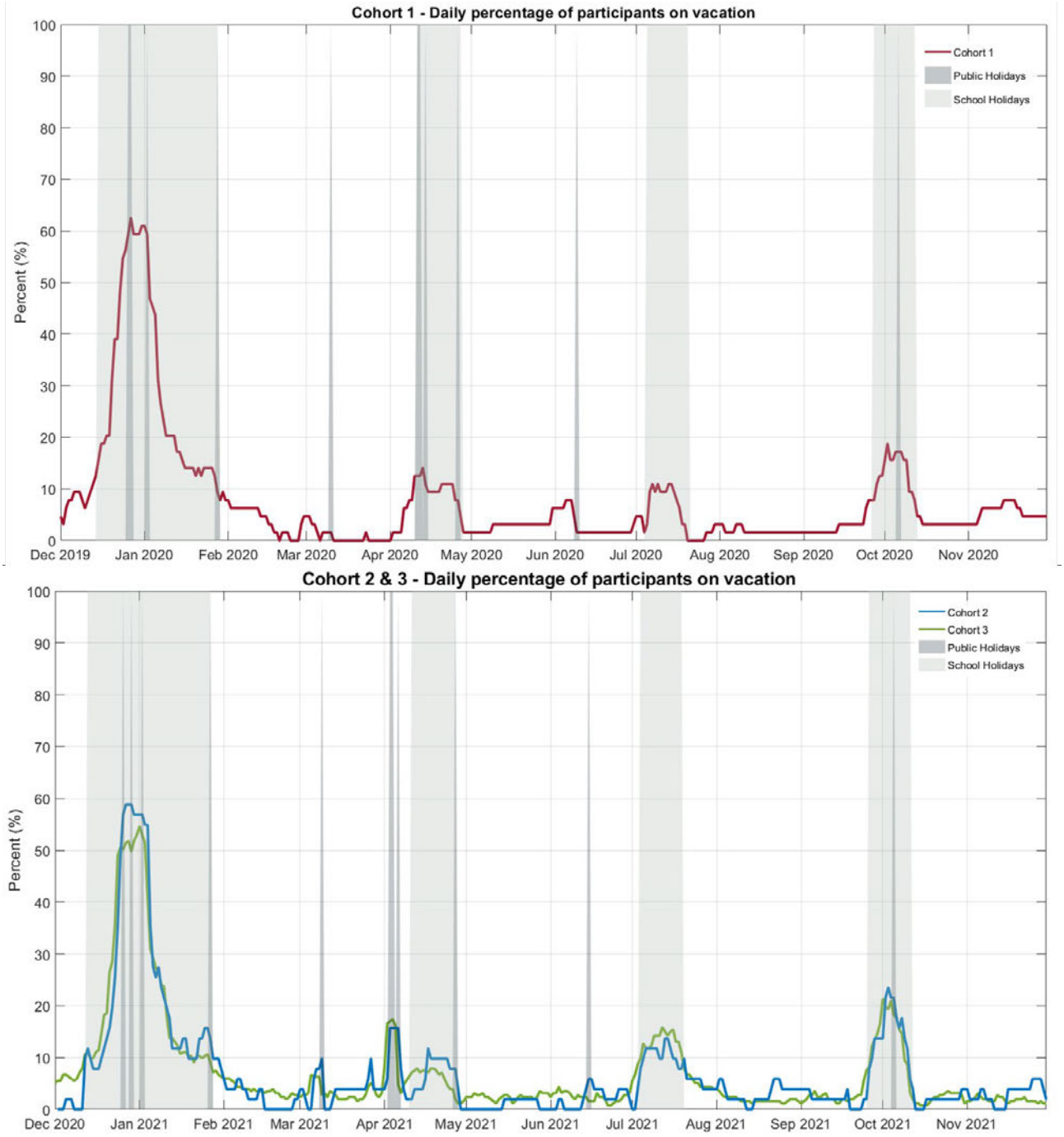


Figure 6.1 - Daily percentage of participants on vacation

6.4.3 Changes in movement behaviours across the vacation period

The average daily minutes spent in sleep, sedentary behaviour, and light, moderate and vigorous physical activity, over the vacation period are shown in Figure 6.2 (detailed results in Appendix 6.4).

Sleep increased significantly during vacation compared with pre-vacation (+21 min/day [95% CI = +19, +24], p<0.001, +4.4% change relative to pre-vacation). This significant increase persisted into the first and second weeks post-vacation (+8 min/day [95% CI = +4, +11], p<0.001, +1.5% and +7 min/day [95% CI = +4, +10], p<0.001, +1.5% respectively) before returning to near-baseline levels.

Sedentary behaviour decreased significantly during vacation compared with pre-vacation (-29 min/day [95% CI = -32, -25], p<0.001, -4.6%). In contrast, post-vacation sedentary behaviour increased significantly from pre-vacation levels (+5 min/day [95% CI = +1, +9], p=0.022, +0.7%).

During and post-vacation time points were all significantly different to pre-vacation levels of light physical activity, however the direction differed. Light physical activity increased during vacation (+3 min/day [95% CI = 0, +5], p=0.021, +0.9%) before decreasing relative to pre-vacation levels and persisting across each post-vacation timepoint (first week = -10 min/day [95% CI = -13,-8] p<0.001, -3.4%; second week = -7 min/day [95% CI = -10, -5] p<0.001, -2.4%; third week = -5 min/day [95% CI = -8, -2] p=0.001, -1.6%; fourth week = -5 min/day [95% CI = -8, -2] p<0.001, -1.7%).

A significant increase in moderate-to-vigorous physical activity occurred during vacation (+5 min/day [95% CI = +3, +6], p<0.001, +13.2%) before returning to pre-vacation levels immediately afterwards.

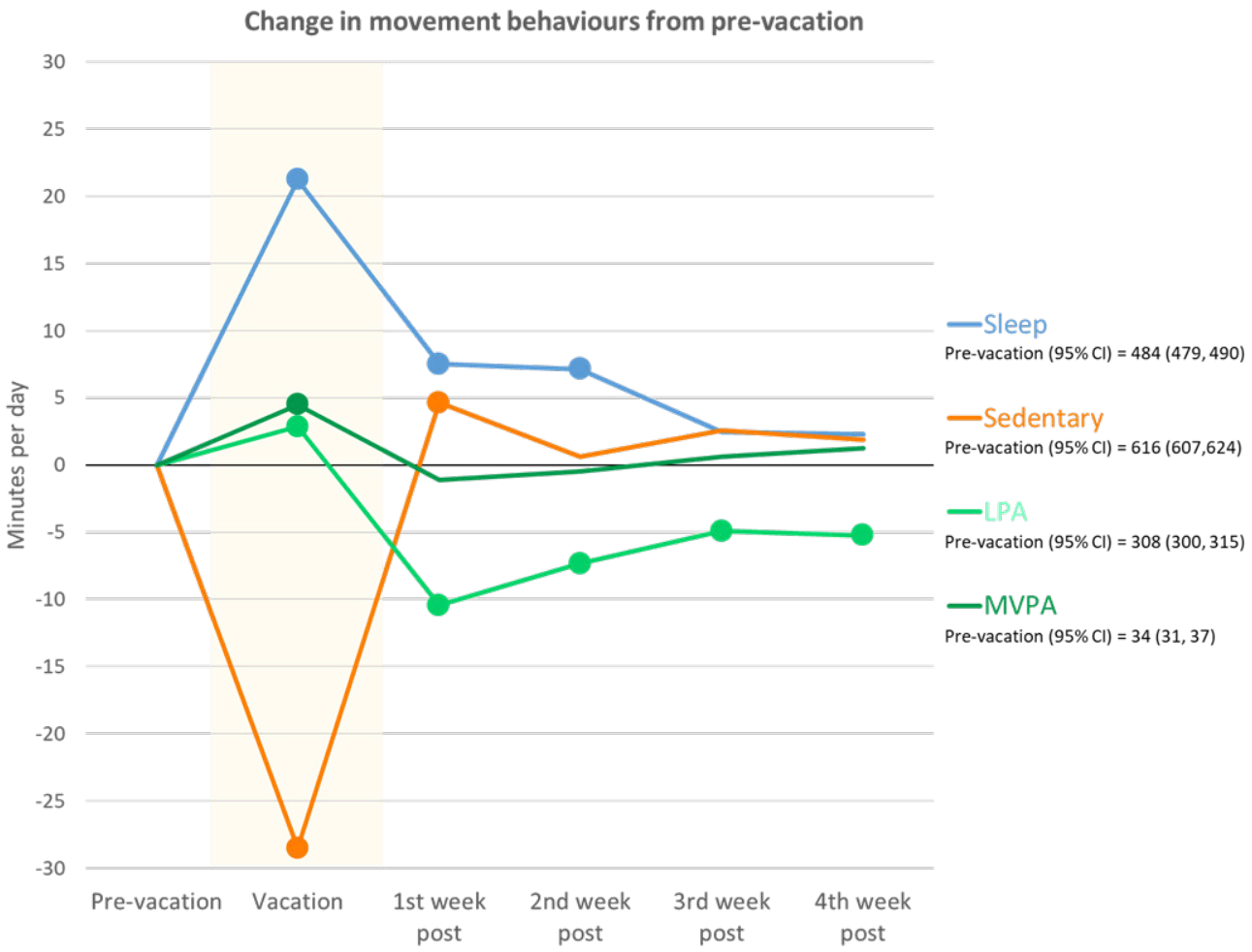


Figure 6.2 - Change in movement behaviours from pre-vacation

Notes: • = significant change from pre-vacation (<0.05). Pre-vacation is calculated as the mean of the 14 days immediately prior to any vacation. Vacation includes any vacation reported (mean length = 12.1 days, standard deviation = 14.1 days). LPA = light physical activity, MVPA = moderate-to-vigorous physical activity. Values reported in Appendix Table 1.

6.4.4 Vacation characteristics associated with changes in movement behaviours

Main vacation purpose

Movement behaviours across the vacation period according to main purpose of the vacation (i.e. family/social events, rest, outdoor recreation and non-leisure) were broadly similar to the overall vacation period patterns (Figure 6.3 and Appendix 6.4). Generally, increases in sleep, reductions in sedentary time, minimal changes in light physical activity, and small increases in moderate-to-vigorous physical activity were observed during vacation. Changes post-vacation appear to persist longer after outdoor recreation and family/social vacations than for rest and non-leisure vacations. Over-correction in the first week post-vacation occurred for sedentary

behaviour after family/social vacations (decrease during, increase post) and light physical activity after outdoor vacations (increase during, decrease post).

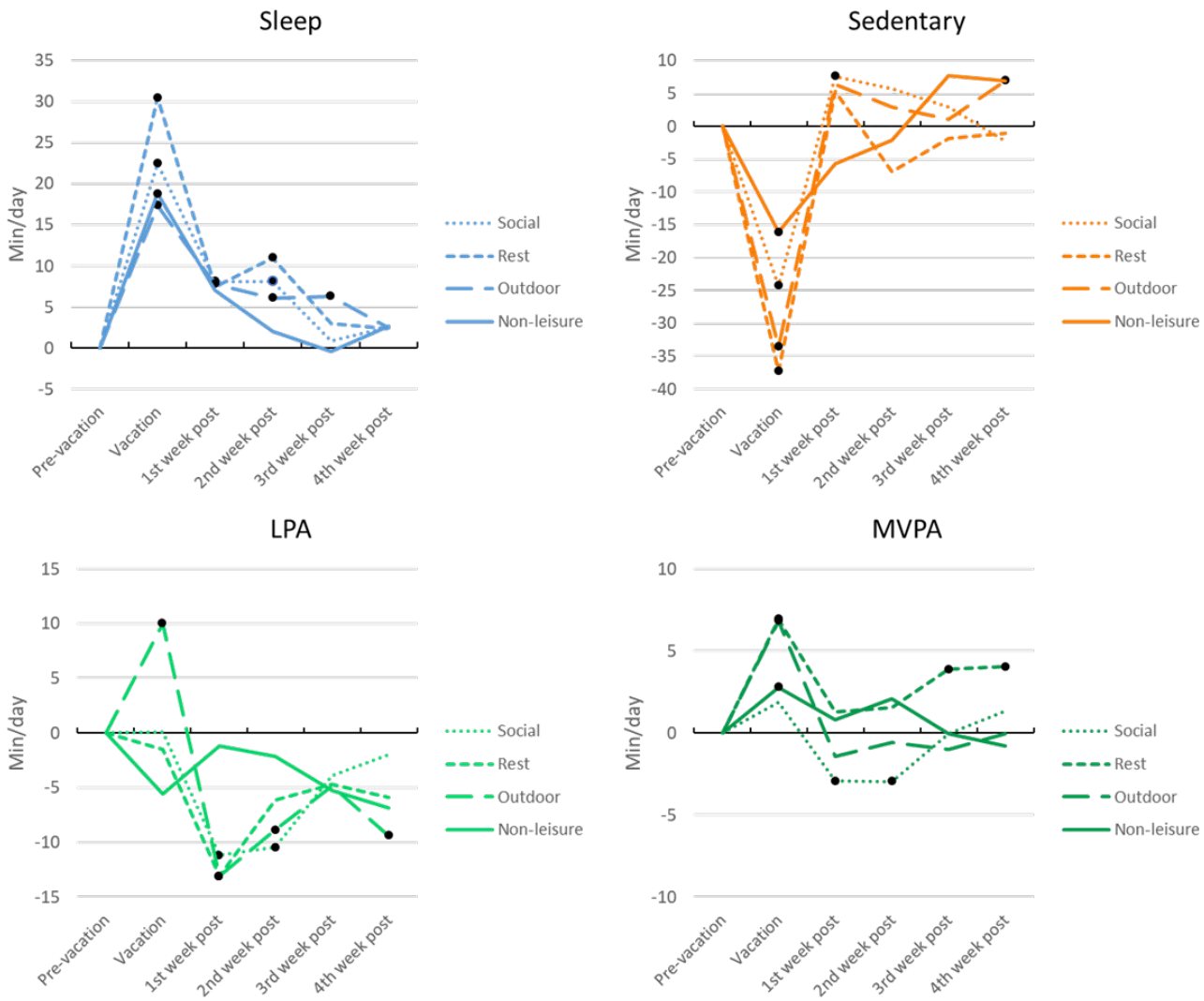


Figure 6.3 - Change in movement behaviours from pre-vacation by type of vacation

Notes: • = significant change from pre-vacation. LPA = light physical activity, MVPA = moderate-to-vigorous physical activity. Values reported in Appendix 6.4. Social = Family or social events, e.g. visiting family, friends, attractions, or attending entertainment events, observing religious or cultural periods (Christmas, Easter), Rest = Rest and relaxation, Outdoor = Outdoor recreation, e.g. hiking, sports, fishing, boating, camping, Non-leisure = non-leisure tasks, e.g. caring for others, household jobs, medical leave.

Vacation length

Movement behaviour changes over the vacation period appeared to differ by vacation length (summarised in Figure 6.4; full details of means, 95% confidence intervals, and p values are provided in Appendix 6.4). Broadly, it appears the longer the vacation, the larger the change

in sleep, and the smaller the change in sedentary behaviour, light and moderate-to-vigorous physical activity. Directions of change during vacation were largely consistent with overall patterns (sleep and physical activity increased, sedentary behaviour decreased, see Figure 2), except for light physical activity during long vacations (>2 weeks) where it decreased significantly by -9 minutes/day (95% CI = -12, -5, p<0.001, -2.8%) from pre-vacation levels. In addition, the longevity of changes seems related to vacation length, with behaviours returning to pre-vacation levels almost immediately after short vacations, whereas changes persisted for several weeks after longer vacations for sleep and light physical activity.

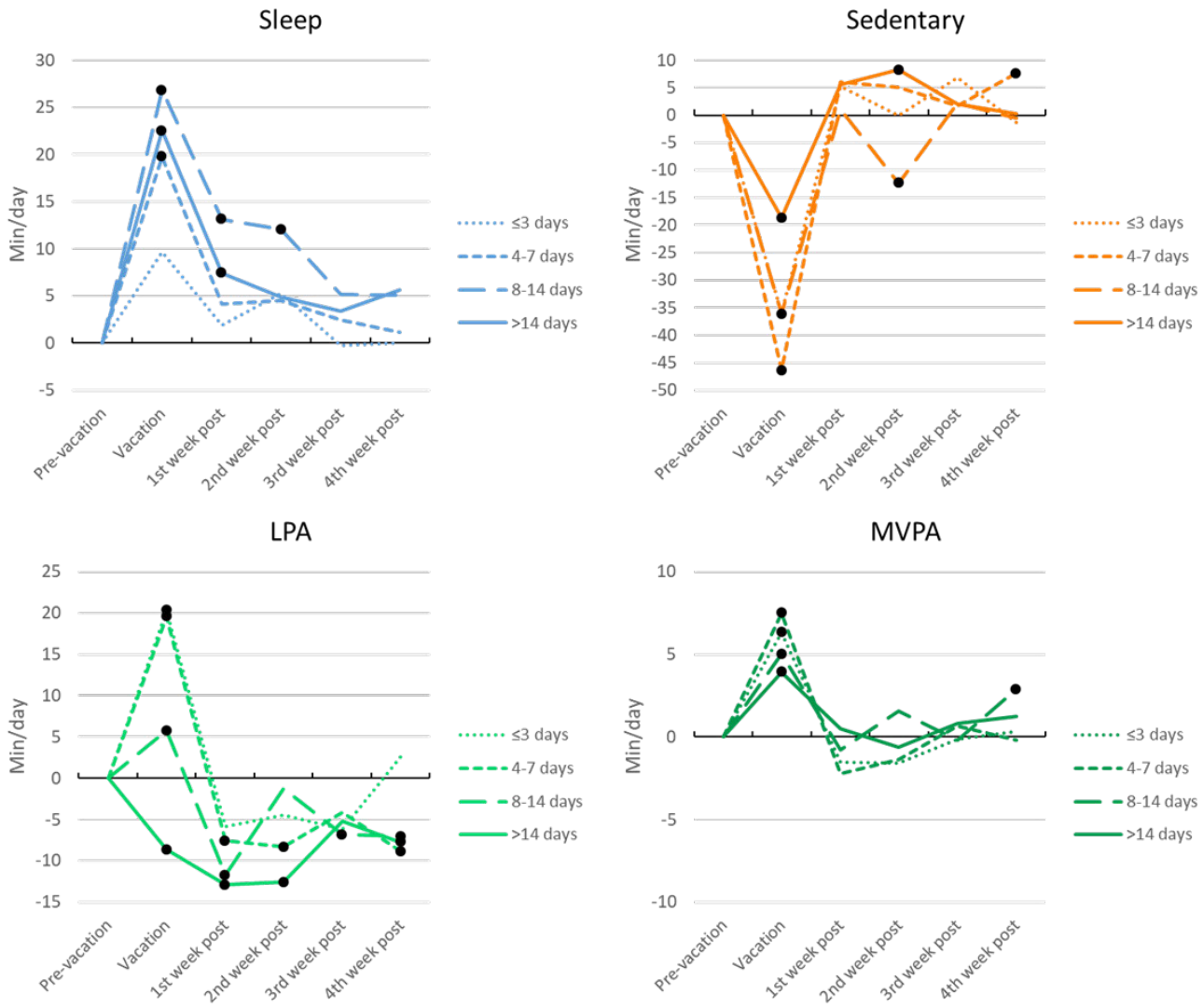


Figure 6.4 - Change in movement behaviours from pre-vacation by length of vacation

Notes: Black markers = significant change from pre-vacation (p<0.05). LPA = light physical activity, MVPA = moderate-to-vigorous physical activity. Values reported in Appendix 6.4.

6.4.5 Sociodemographic and occupation characteristics associated with changes in movement behaviours across the vacation period

Appendix 6.4 contains results of interaction effects of participants' sociodemographic and occupation characteristics on movement behaviours during vacation. The changes in daily movement behaviours during vacation were unrelated to sociodemographic characteristics such as sex, age, education level, BMI, health status, occupational characteristics, and baseline activity levels. No comparisons were statistically significant post-Bonferroni corrections.

6.5 Discussion

6.5.1 Principal findings

Across all vacations, participants' movement behaviour patterns changed significantly in favourable directions (i.e., increased physical activity, decreased sedentary behaviour). The duration of vacation and type of vacation appeared to be associated movement behaviour changes, with vacations of 4 days to 1-2 weeks and outdoor recreation vacations associated with the most favourable changes. The largest significant during vacation changes were seen for vacations of >1 week duration. Additionally, after vacations of >1 week duration, sleep remained higher and light physical activity lower than pre-vacation for at least the first week. Finally, participant characteristics did not appear to influence changes in movement behaviours during or after vacation.

This study is the first to explore movement behaviours across the 24-hour day using a longitudinal design with objective measures. Our findings were consistent with the two previous studies using self-reported measures. For example, de Bloom et al [204] reported an increase in vacation sleep duration for vacations of longer than two-weeks. Of note, the change was almost twice as large as the current study (+42 min/day vs +23 min/day), which may be due to the method of measuring sleep. Furthermore, our findings for increased physical activity and decreased sedentary behaviour during vacation were broadly consistent with those reported by Cooper et al [205], who reported non-significant trends, rather than significant findings as found in the current study. This may be due to the sample size, since

the Cooper study involved 122 participants, which was less than half the sample size in our study.

The most consistent favourable changes across movement behaviours occurred in the 4 days to 2-week range, with these changes appearing to persist longer, the longer the vacation. This is consistent with the law of inertia, where people have set patterns of time use which are difficult to perturb.[162] When a perturbation does occur, the tendency is for behaviour to snap back to initial patterns once the short-term disruption (i.e. a vacation) is removed.[162] The longer the disruption, the greater the change, and the slower the return to pre-existing levels.[162]

When considering the type of vacation, outdoor recreation was the only category where all movement behaviours had significant favourable changes during vacation. This may be because outdoor recreation vacations are ideally suited to physical activity with two important facilitators, the natural environment and free time, available in abundance.[213] Further, increased physical activity has been shown to have a positive effect on sleep quality, particularly duration.[214, 215]

Most participants in this study worked in office-based occupations, on a Monday-to-Friday schedule. The large decrease in sedentary behaviour from weekdays to weekends is consistent with previous literature of office workers[182] and is also observed in the change from pre-vacation to during vacation. The opposite change occurred for sleep and physical activity, with both increasing on weekends and during vacations, relative to weekdays and pre-vacation respectively. The overall consistent effect of weekends and vacations on movement behaviours is likely a product of people not needing to go to work, removing long hours of sedentary employment, and increasing time available to freely allocate across movement behaviours. This would suggest vacations are like very long weekends. When considering post-vacation, the over-correction in sedentary behaviour observed during the first week, where it was significantly increased, may be attributed to a workload catch-up, where tasks accumulated during vacation may need to be added to usual work demands.[216]

6.5.2 Strengths and limitations

To our knowledge, this is largest ever study of movement behaviour patterns during vacations, as well as the first study of vacations that captures 24-hour objective movement behaviour data. Use of a remote data collection method meant there were minimal barriers to participants' involvement in the study when away from home.

This study explored activity behaviour patterns exclusively, with minimal knowledge of participant motivations, vacation destinations, itineraries or vacation companions. This sample had a high concentration of vacations during the Australian summer (December and January) and it is possible the time of year when a vacation is taken may be associated with movement patterns, however, this was beyond the scope of the current study. The study sample was generally representative of middle-aged Australians. However, as the sampling frame was parents of primary school age children, when compared with national population data there were slight over-representation of people who were married / in de facto relationships, parents, employed persons and those with higher education. It must be acknowledged that the participants were all parents and city-dwellers residing in one major Australian city, and that the generalisability of the findings, especially for adults without children (approximately 23% of middle aged Australians) and those who reside in non-urban areas (14% of Australians) is unclear. The statistical analyses used in this study explored the 24-hour day using individual models without direct comparison between movement behaviours. An alternative and more complex approach to account for direct interactions would be compositional data analysis. Whilst the sample size is adequately powered for overall analyses, it's possible sub-group analyses on participant characteristics may be underpowered. Finally, data collection occurred during the COVID-19 pandemic. Importantly, within state travel was minimally impacted in South Australia during the study period. However, interstate and international travel was largely restricted. Australia adopted an elimination approach to the virus with widespread and varied border closures along with strict quarantine rules, adding up to two additional weeks to any cross-border travel. Participant choices of vacation destination, duration and vacation activities are likely to have differed from pre-COVID travel.

6.5.3 Implications

Whilst the findings of this study suggest there may be an optimal length and type of vacation to yield the greatest favourable changes, the availability of vacation leave will ultimately dictate vacation options. Minimum yearly paid leave entitlements vary widely around the world. In Australia, the minimum is 4 weeks,[217] whereas some European countries are higher (e.g. 6 weeks in France [217]). The US has no minimum paid leave requirements,[218] though about three-quarters of US workers receive 2-3 weeks of paid leave.[219] Workers in countries with low allocations, such as the US, may prefer multiple short breaks, rather than a single 2-week block each year. Conversely, high allocation countries such as France, allow for multiple 2-week vacations per year, where potentially favourable changes may be repeated and spread across the year. Additionally, leave availability may influence vacation type as some options may not be feasible on short breaks where travel time to the destination is prohibitive.

6.5.4 Future directions

Changes observed during vacation are likely the result of a combination of factors, specific to each vacation. Whilst it is difficult to replicate this outside of the vacation setting, potential exists for interventions around the vacation. Future research should include experimental study designs, exploring interventions that encourage favourable behaviour change in the lead up to or after vacations. An interesting finding from the current study is the over-correcting of sedentary behaviour and light physical activity post-vacation toward less favourable directions which would suggest interventions aimed at reducing sedentary behaviour and increasing light physical activity at this timepoint may be warranted. There is potential to explore what specific behaviours a person engages with during vacation (i.e., increased walking, earlier bedtime) that likely produced favourable changes and aim to incorporate these habits into daily life post-vacation. Another important consideration is exploring potential changes in mental health and well-being during vacation and how they are associated with movement behaviours. Exploring sleep changes in chronic under-sleepers would be of interest to observe if the same increases in sleep duration observed in this study are replicated in that population. Finally, a larger sample or a sample followed for a longer duration would allow more in-depth explorations into particular sub-groups identified within this study, i.e. vacation purpose, demographic subgroups.

6.6 Conclusion

During vacations, favourable changes in movement behaviours (i.e, more physical activity and less sedentary behaviour) were observed, with these changes most pronounced in vacations of 4 days to 2 weeks long, and during vacation for outdoor recreation. Post-vacation, moderate-to-vigorous physical activity quickly returned to pre-vacation levels whereas sedentary behaviour and light physical activity tended to over-correct. Increases in sleep were apparent for around two weeks post-vacation, particularly after vacations longer than one week, and after outdoor and social vacations. These data provide preliminary evidence of the health benefits of vacations. Findings suggest that interventions timed immediately post-vacation may help combat unfavourable over-corrections observed in sedentary behaviour and light physical activity.

6.7 Declarations

Ethics approval and consent to participate

Ethics approval was provided by the University of South Australia Human Research Ethics committee (UniSA HREC, Protocol number: 201901) and participants provided written, informed consent prior to commencing participation.

Consent for publication

Not applicable

Availability of data and materials

Data used in the current study are available and may be obtained from the corresponding author upon reasonable request.

Competing interests

The authors report no conflict of interest

Funding

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Authors' contributions

TF, CM, RC and FF were responsible for study inception and design. TF consolidated and cleaned data for analysis. All authors contributed to the statistical analysis plan with TF conducting the analyses. TF led manuscript writing and all authors conducted a critical revision and provided substantive feedback on the manuscript, in addition to approval of the final version.

Acknowledgements

Not applicable

Chapter 7

Discussion

The preceding chapters of this thesis have explored the temporal context of movement-related behaviours. This chapter will summarise the main findings of the four original studies and provide an overall message of these combined results. It will highlight the key contributions of the work presented in this thesis, and finally, future research directions related to the temporal nature of movement-related behaviour patterns will be discussed.

7.1 Summary of key findings

The overarching aim of this thesis was to explore the temporal cycles in sleep, sedentary behaviour and physical activity in adults over a year-long timescale, as well as their variation around certain events (e.g. vacations Christmas-New Year and daylight saving time transitions). This aim was addressed using a combination of primary and secondary research.

7.1.1 Systematic review of current literature

A systematic review and meta-analysis of longitudinal research exploring temporal events and movement behaviours was completed. Results of the systematic review highlighted the lack of published longitudinal research exploring the temporal associations of movement behaviour patterns. Seventeen studies were included, with most exploring seasonal changes (n=11), along with Ramadan (n = 4). Only single studies were identified exploring the impact of vacations (n=1) and daylight saving time transitions (n=1). Across 16 meta-analyses only one had significant findings ($p<0.05$) with light physical activity lower than the yearly average in winter. Overall, very few studies used long-term, device-based activity measurement. Most device-based studies record continuously for 7-14 days, and longitudinal change was assessed through multiple measurement timepoints. The remaining study chapters explored data collected during the ARIA study.

7.1.2 ARIA-based studies

The studies using the ARIA data described year-long movement behaviour patterns and explored associations of movement behaviours with specific temporal cycles and events. These included days of the week, seasonal cycles, daylight saving time transitions, Christmas-New Year period, weather and vacations. Key findings from the studies exploring the ARIA cohort are summarised below:

<u>Sleep</u>

Sleep was longest on weekends, during cooler months (in winter and autumn), during and shortly after the Christmas-New Year period, and during and immediately after vacation. Conversely, sleep was the shortest as the weekdays progressed, after daylight saving time started, during summer and as temperatures rose (see Figure 7.1). Annual patterns followed a roughly sinusoidal wave pattern with peaks in winter months and troughs during summer

months, the exceptions being brief spikes at the New Year and the start of October. Sleep varied by approximately 30 min/day (or 6%) of the yearly mean.

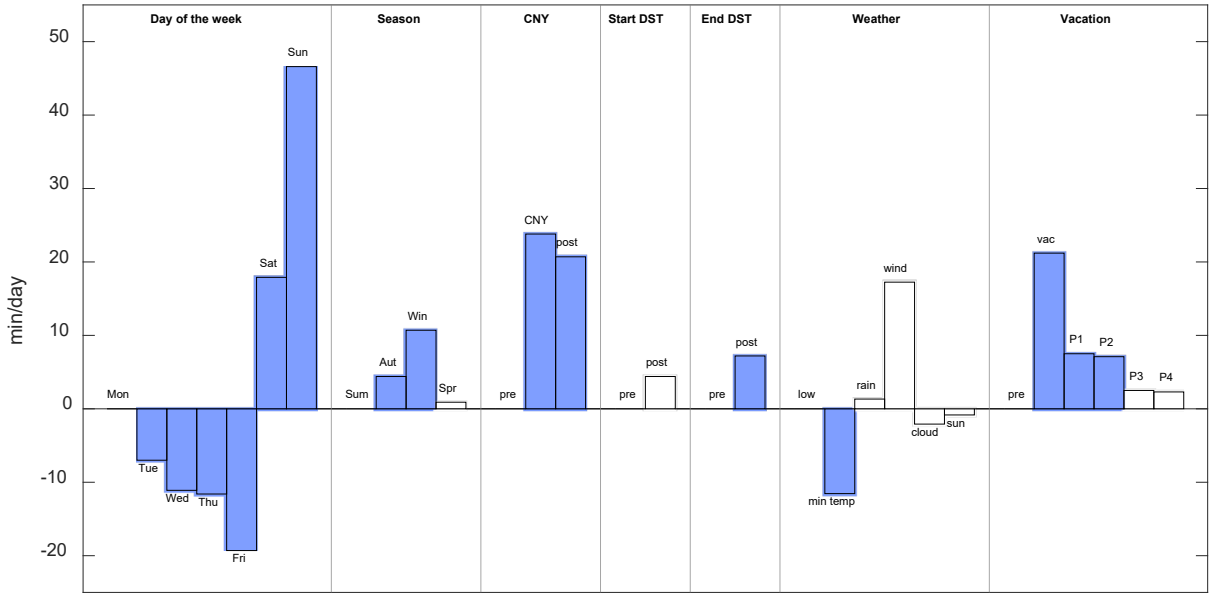


Figure 7.1 – Change in sleep duration associated with temporal cycles and events

Notes: Results presented as change from comparator (Day of the week = Mon, Season = Sum, CNY/Start DST/End DST/Vacation = pre and Weather = low, i.e. minimum value of weather variable). Significant associations shown in blue ($p<0.05$) and non-significant associations in white ($p\geq0.05$). Weather results are presented as change across range and presented as predicted change at maximum weather values. Aut = autumn, cloud = highest daily cloud cover, CNY = Christmas – New Year period, DST = daylight saving time, Fri = Friday, low = lowest value of weather variables, Mon = Monday, min temp = highest daily minimum temperature, P1 = 1st week post vacation, P2 = 2nd week post vacation, P3 = 3rd week post vacation, P4 = 4th week post vacation, post = period after temporal event, pre = period prior to temporal event, rain = highest daily rainfall, Sat = Saturday, Spr= spring, Sum = summer, Sun = Sunday, sun = sunshine, Thu = Thursday, Tue = Tuesday, Vac = vacation, Wed = Wednesday, Win = winter, wind = highest daily wind speed.

Sedentary behaviour

Sedentary behaviour was longest on weekdays post-Monday, during winter, after the Christmas-New Year period relative to before, after daylight saving time ended, as minimum temperature and wind speed increased, and immediately after vacation relative to before. Conversely, sedentary behaviour was shortest on weekends, as daily hours of sunshine increased, and during vacations. Interestingly, there was relatively little seasonal variation in the duration of sedentary behaviour across the whole year (see Figure 7.2). This is similar to the annual patterns where the majority of the year remained within ±5 min/day (±1%) of the yearly average except for a brief trough of approximately -35 min/day (-6%) around the New Year. Overall, the weekend-weekday cycle, and the change during vacations, dominated the overall variability in sedentary behaviour duration.

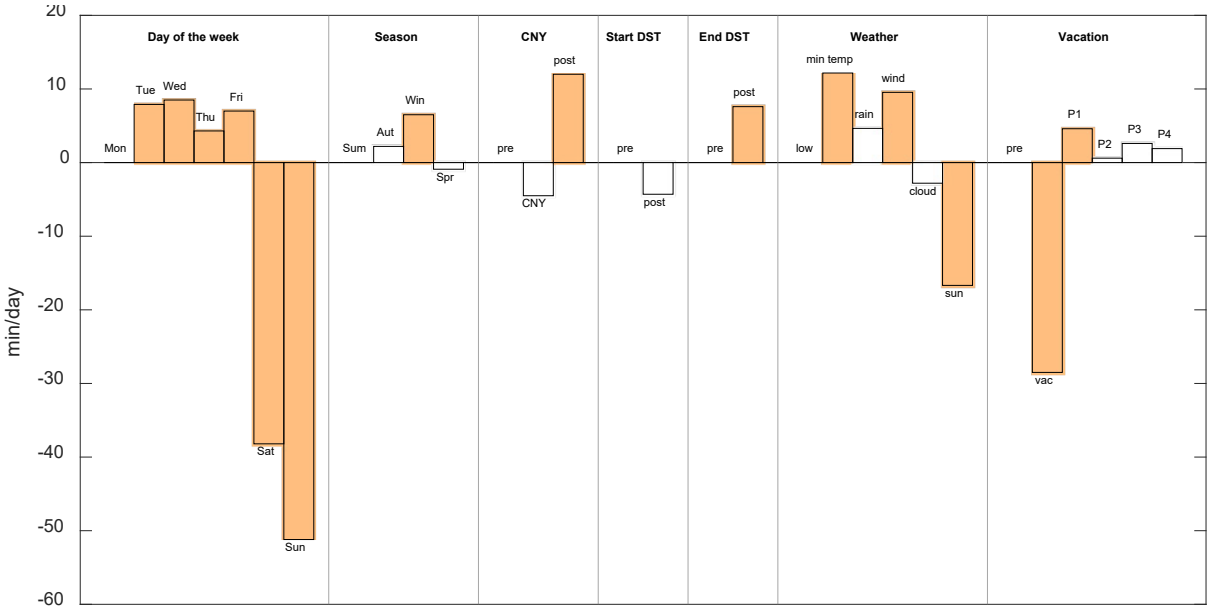


Figure 7.2 - Change in sedentary behaviour duration associated with temporal cycles and events

Notes: Results presented as change from comparator (Day of the week = Mon, Season = Sum, CNY/Start DST/End DST/Vacation = pre and Weather = low, i.e. minimum value of weather variable). Significant associations shown in orange ($p<0.05$) and non-significant associations in white ($p\geq0.05$). Weather results are presented as change across range and presented as predicted change at maximum weather values. Aut = autumn, cloud = highest daily cloud cover, CNY = Christmas – New Year period, DST = daylight saving time, Fri = Friday, low = lowest value of weather variables, Mon = Monday, min temp = highest daily minimum temperature, P1 = 1st week post vacation, P2 = 2nd week post vacation, P3 = 3rd week post vacation, P4 = 4th week post vacation, post = period after temporal event, pre = period prior to temporal event, rain = highest daily rainfall, Sat = Saturday, Spr= spring, Sum = summer, Sun = Sunday, sun = sunshine, Thu = Thursday, Tue = Tuesday, Vac = vacation, Wed = Wednesday, Win = winter, wind = highest daily wind speed.

Light physical activity

Light physical activity was longest Wednesday through Saturday, as minimum temperature, sunshine and cloud cover increased, and during vacations. Conversely, light physical activity was lowest during cooler months (autumn and winter), during and shortly after the Christmas-New Year period, as the wind speed increased, and in the month after vacation relative to before vacation (see Figure 7.3). Annual patterns show the overall variability was within approximately ±22 min/day (±7%) of the yearly mean. Specifically, light physical activity was generally above average from November to March, and below average from April to October, with a brief peak around the Christmas to New Year period and a brief trough in late July.

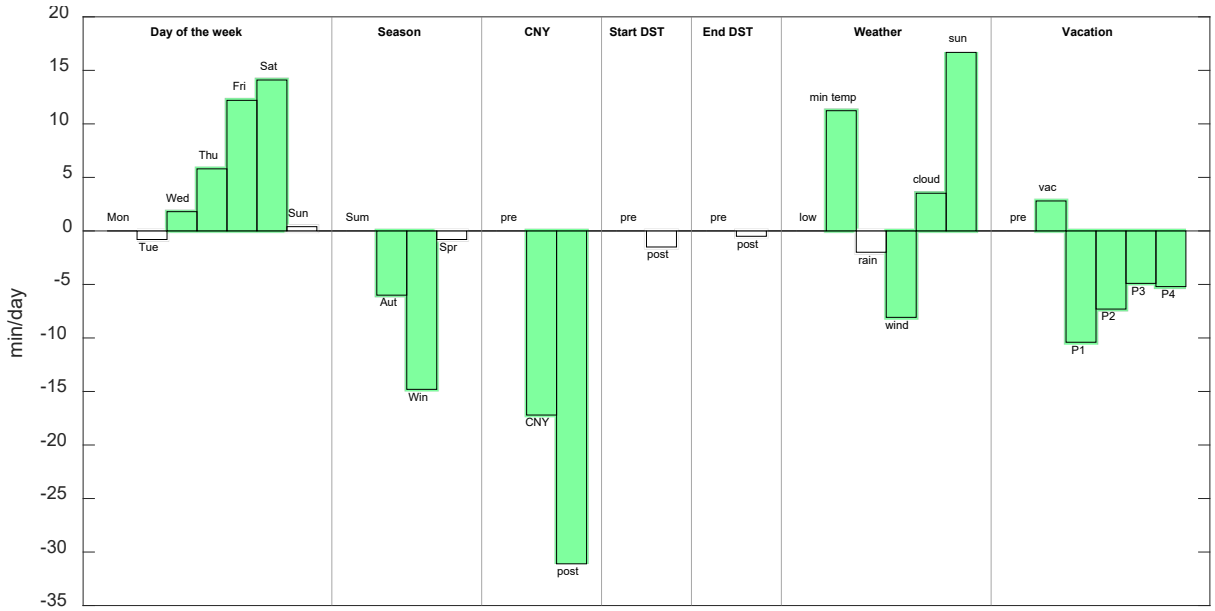


Figure 7.3 - Change in light physical activity duration associated with temporal cycles and events

Note: Results presented as change from comparator (Day of the week = Mon, Season = Sum, CNY/Start DST/End DST/Vacation = pre and Weather = low, i.e. minimum value of weather variable). Significant associations shown in light green ($p<0.05$) and non-significant associations in white ($p\geq0.05$). Weather results are presented as change across range and presented as predicted change at maximum weather values. Aut = autumn, cloud = highest daily cloud cover, CNY = Christmas – New Year period, DST = daylight saving time, Fri = Friday, low = lowest value of weather variables, Mon = Monday, min temp = highest daily minimum temperature, P1 = 1st week post vacation, P2 = 2nd week post vacation, P3 = 3rd week post vacation, P4 = 4th week post vacation, post = period after temporal event, pre = period prior to temporal event, rain = highest daily rainfall, Sat = Saturday, Spr= spring, Sum = summer, Sun = Sunday, sun = sunshine, Thu = Thursday, Tue = Tuesday, Vac = vacation, Wed = Wednesday, Win = winter, wind = highest daily wind speed.

Moderate-to-vigorous physical activity

Moderate-to-vigorous physical activity tended to be longest on weekends, during milder sunny weather (spring and increased sunshine) and on vacation. Moderate-to-vigorous physical activity tended to be shortest during winter and weather extremes (increased rain, wind, and minimum temperature, and very high or low maximum temperature; see Figure 7.4). Annual patterns tend to be relatively stable, being within approximately ±2 min/day (or ±6%) of the yearly mean with a few short fluctuations up to ±4 min/day (±11%) of the year mean.

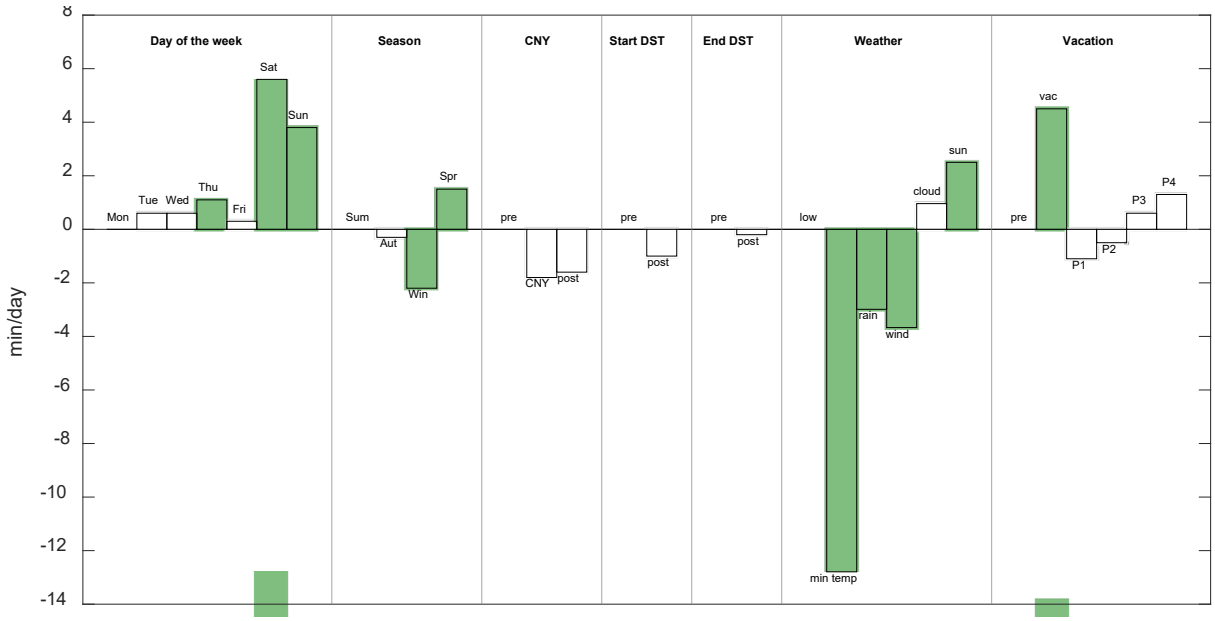


Figure 7.4 - Change in moderate-to-vigorous physical activity duration associated with temporal cycles and events

Note: Results presented as change from comparator (Day of the week = Mon, Season = Sum, CNY/Start DST/End DST/Vacation = pre and Weather = low, i.e. minimum value of weather variable). Significant associations shown in green ($p<0.05$) and non-significant associations in white ($p\geq0.05$). Weather results are presented as change across range and presented as predicted change at maximum weather values. Aut = autumn, cloud = highest daily cloud cover, CNY = Christmas – New Year period, DST = daylight saving time, Fri = Friday, low = lowest value of weather variables, Mon = Monday, min temp = highest daily minimum temperature, P1 = 1st week post vacation, P2 = 2nd week post vacation, P3 = 3rd week post vacation, P4 = 4th week post vacation, post = period after temporal event, pre = period prior to temporal event, rain = highest daily rainfall, Sat = Saturday, Spr= spring, Sum = summer, Sun = Sunday, sun = sunshine, Thu = Thursday, Tue = Tuesday, Vac = vacation, Wed = Wednesday, Win = winter, wind = highest daily wind speed.

7.2 Overall message

Together, these results form a consistent picture: daily sleep, sedentary behaviour and physical activity patterns fluctuate around society-level events, and these changes are overlaid on a year-long rhythm associated with societal (i.e. intra-week) and natural (i.e. seasonal) cycles. This interplay suggests fluctuations may have differing associations depending on the overlap of temporal factors, i.e. when a temporal event (e.g. a vacation) occurs relative to the phase of a temporal cycle (e.g. season). Furthermore, the temporal windows of the largest potentially favourable associations occurred at different periods for different movement behaviours. For example, weekends, Christmas-New Year and vacations had the largest increases in sleep; the day of the week and vacations had the largest decreases in sedentary behaviour; Christmas-New Year had the largest increase in light

physical activity; and several weather variables had the largest decreases for moderate-to-vigorous physical activity.

The focus of reporting on movement-related behaviours has largely been on overall average change. However, consideration should also be given to the clinical relevance of the results in this thesis. Many of the temporal changes identified were small and arguably not of clinical significance when considering, on average, participants in the ARIA study met sleep and moderate-to-vigorous physical activity guidelines. It is worth considering, however, that there are potentially meaningful findings when considering different subgroups where magnitudes of change are likely to have differed. For example, the impact of unfavourable changes at specific timepoints may be problematic for those with underlying poor movement behaviour distribution (e.g. those not meeting guidelines). Additionally, whilst the changes at daylight saving transitions were relatively small, there is clear literature showing detrimental outcomes (e.g. increase in vehicle and at-home accidents[161]) around these timepoints, so these seemingly small changes may have clinical meaning. Overall, these findings have provided a variety of new contributions to the largely unexplored temporal nature of intra-annual 24-hour movement behaviour patterns.

7.3 Key contributions

This program of work provides comprehensive longitudinal research examining the intra-year temporal disruptors of daily movement behaviour patterns, a relatively under-researched topic. It created and interrogated a unique and highly detailed dataset comprising 13 months' continuously measured minute-by-minute movement behaviour data. To our knowledge, this dataset is one of the first to capture ongoing data regarding 24-hour daily movement patterns. These data were collected using purpose-built software, allowing for minute-level data to be collected cheaply, a task that would be prohibitively expensive using commercial software in this sample size over such long periods. Finally, a wide variety of temporal cycles and events were explored. Most of the included comparisons have not been previously analysed with such a detailed dataset in a sample of this size. The findings reported in this thesis provide new insight into the magnitude and duration of movement pattern changes associated with a variety of temporal disruptors. Thus, this thesis represents the early stages of a new

methodological paradigm for exploring movement behaviours. My studies demonstrate that this methodological approach is feasible, with high participant compliance and acceptability, and is relatively cost-effective when compared with research-grade measurement options. This body of work is a precursor for several avenues of future research.

7.4 Future directions

7.4.1 Wider exploration of temporal disruptors

The body of work presented in this thesis has focused on temporal cycles and events that are typically experienced by society at large each year. The events compared here are not exhaustive and could be expanded on in future research. Examples include school holidays, religious periods such as Easter and Ramadan, or hours of daylight. Furthermore, different geographic or climatic regions are likely to have differing associations with weather and seasons. Additionally, a population's cultural or religious festivals will differ from country to country. Future research, using a similar methodological approach, should target larger, more socio-demographically- and geographically-diverse samples. Consideration should also be given to exploring the temporal nature of additional health-related measures and how they are associated with movement patterns.

This thesis focused on daily movement data, however the ARIA study captured a variety of other health behaviour and health outcome data such as weight, diet, mental health and wellbeing. Exploring the temporal context of these additional measures may yield similar temporal patterns to movement data or reveal new associations. For example, weight gain over the Christmas-New Year period has been identified in previously literature,[220, 221] along with seasonal patterns to dietary intake.[222] Interrogating these outcomes alongside movement patterns is warranted. Fluctuations in movement patterns throughout the ARIA study period present potential challenges when aiming to effectively measure "typical" movement behaviours.

7.4.2 Implications for measurement

The results in this thesis have highlighted the variation in movement behaviour patterns across a year-long measurement period. Collecting continuous data for a year is uncommon

and unfeasible for many study designs. This presents an important consideration when aiming to capture “typical” movement of participants, as the timing and length of measurement period may bias results.

The size of the fluctuations observed varied across the associations tested and on visual inspection of year-long patterns. For example, the largest fluctuations appeared to be across the days of the week with weekday vs weekend appearing to be a clear differentiator. That would suggest a minimum of a full 7-day week would be recommended. Further to this, owing to their co-dependent nature, behaviours cannot follow the same fluctuations across the year. Each movement-related behaviour had unique associations with the temporal events and cycles explored in this thesis, suggesting that the timing and length of measurement cannot be optimal for all behaviours equally.

When interested in reporting “typical” movement, it is largely a question of what variability is acceptable for the research being undertaken. If “typical” yearly movement is needed, then clearly measuring for an entire year will yield the truest results, yet this is not always feasible. If the results are to be representative of "typical” patterns, then an acceptable tolerance is needed and largely arbitrary without further exploration of longitudinal datasets such as the one used in this thesis. Consideration should also be given to how the length and timing of device-measured movement patterns may influence population-level surveillance.

If a population is measured across the year, yet participants only provide one week of data, the temporal context differs across participants with potentially varied temporal associations. It is likely that longer periods of surveillance may be needed for more accurate population estimates, yet this is not necessarily cost effective or feasible at present and may pose challenges for maintaining participant compliance as measurement durations increase. However, with the rapidly evolving wearables industry producing cheaper and more accurate devices, and as wearables become more pervasive and acceptable amongst the general population, there is potential to either implement wearables widely in future research or tap into the data already being captured by society at large in the form of citizen science projects.

7.4.3 Citizen science with wearables

In the ARIA study we gave 375 people Fitbit activity trackers. However, there are millions of Australians already using Fitbit and other brand wearable devices to capture their movement data.[223] This is generating incredible amounts of movement data each day. There is vast potential to gather ongoing data by using already owned devices, without providing the device to research participants in the first instance. This approach has the potential to deliver a massive cost saving for conducting movement behaviour research. A potentially valuable approach to harnessing these data is through citizen science.

Citizen science refers to research which is a collaboration between scientists and the general public who voluntary collect data, help identify areas of concern and priority, and contribute to making interventions as impactful as possible for the target community.[224] Engaging the public in movement behaviour surveillance and interventions, whilst tapping into these data, is a potentially valuable collaboration ready to be undertaken. This approach will not only upscale the volume of movement data available for a target population, but collaborating directly with the people who will be the target of public health interventions will mean the areas of movement-related health of most relevance to those individuals can be prioritised. At scale this approach does present technical and logistical challenges, including database management, data storage and data security. While these challenges will need to be addressed in future research, another approach to optimising interventions is considering the timing of public health promotion initiatives.

7.4.4 Temporal considerations for public health promotion

Generally, public health messaging has focused on geographics (e.g. rural and remote regions), demographics (e.g. age-group or ethnicity) or socioeconomics (e.g. low socioeconomic status groups). An often-overlooked consideration is the timing of when the health initiative is delivered. This thesis has highlighted periods of fluctuations that may be of benefit for health messaging. For example, winter appears to be a time of less light physical activity and moderate-to-vigorous physical activity and more sedentary behaviour. Similarly, moderate-to-vigorous physical activity declines as overnight temperatures rise and daily maximums are at their highest. These temperatures are typically during summer months. By identifying these periods as being associated with potentially unfavourable movement patterns, health messaging can be timed when the messaging may be of the most benefit. Like timing of interventions and public health messaging to optimise outcomes, an emerging

methodology known as just-in-time adaptive interventions for movement patterns is worth exploration.

7.4.5 Just-in-time adaptive interventions

Just-in-time adaptive interventions are interventions that adapt the intervention intensity, content and timing to the individual's personal context, aiming to deliver an intervention at the time it is most needed or when the participant is mostly likely to be receptive to engage.[185] For example, a participant may be asked a simple rating question on mental health symptoms daily using a mobile app and when scores suggest their mental health is in decline, an intervention may be deployed in response. There is potential to apply this methodological approach to movement patterns.

In the context of movement patterns, there is potential to use data captured from wearable devices to identify unfavourable changes to movement patterns over time without needing to engage the participant first. This may identify unfavourable patterns associated with the temporal cycles or events identified in this thesis or patterns unique to the individual. Additionally, movement data may be combined with self-report tools such as questionnaires or diaries where a participant may be able to identify timepoints of altered movement patterns (e.g. an injury or illness) in real-time, enhancing the detail of a participant's movement data. By capturing 24-hour movement over time, historical patterns may be helpful for predicting future unfavourable trends in movement behaviour and interventions may be deployed pre-emptively to mitigate this. Also, a potentially useful addition is weather forecasting, where predicted weather can be matched to predicted movement patterns using generalised average results as reported here, or from person-specific historical movement data. The data captured by wearable devices provide vast potential to support health.

Wearable devices are widely used by the general population, generating incredible amounts of data each day. Deploying big data computational approaches such as machine learning and artificial intelligence are rapidly improving, which will assist in bringing these potential interventions to fruition. Importantly, with these advancements brings new challenges. Future research using wearable technology will require exponentially larger digital storage along with

increasingly sophisticated privacy and security measures to protect participant data. Ongoing research in this space will be highly interdisciplinary, to address these challenges.

7.5 Conclusion

The temporal context of movement-related behaviour changes has been largely overlooked. This thesis has demonstrated a dual-layered association between movement behaviours and temporal disruptors. Specifically, patterns appear to fluctuate around temporal events, such as the Christmas-New Year period and vacation, and these are overlaid on a year-long rhythm of temporal cycles, such as intra-week and seasonal cycles. Future research using big data will expand the knowledge base of temporal patterns in movement behaviours and related health outcomes, improving our understanding of the "when" of unfavourable movement patterns. In the future, capitalising on this information using citizen science and just-in-time adaptive intervention approaches may support the delivery of interventions at the time they are needed most.

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Appendices

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Annual, seasonal, cultural and vacation patterns in sleep, sedentary behaviour and physical activity: a systematic review and meta-analysis

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Abstract

Background: Time spent in daily activities (sleep, sedentary behaviour and physical activity) has important consequences for health and wellbeing. The amount of time spent varies from day to day, yet little is known about the temporal nature of daily activity patterns in adults. The aim of this review is to identify the annual rhythms of daily activity behaviours in healthy adults and explore what temporal factors appear to influence these rhythms.

Methods: Six online databases were searched for cohort studies exploring within year temporal patterns (e.g. season effects, vacation, cultural festivals) in sleep, sedentary behaviour or physical activity in healthy 18 to 65 year old adults. Screening, data extraction, and risk of bias scoring were performed in duplicate. Extracted data was presented as mean daily minutes of each activity type, with transformations performed as needed. Where possible, meta analyses were performed using random effect models to calculate standardised mean differences (SMD).

Results: Of the 7009 articles identified, 17 studies were included. Studies were published between 2003 and 2019, representing 14 countries and 1951 participants, addressing variation in daily activities across season ($n = 11$), Ramadan ($n = 4$), vacation ($n = 1$) and daylight savings time transitions ($n = 1$). Meta analyses suggested evidence of seasonal variation in activity patterns, with sleep highest in autumn (+ 12 min); sedentary behaviour highest in winter (+ 19 min); light physical activity highest in summer (+ 19 min); and moderate to vigorous physical activity highest in summer (+ 2 min) when compared to the yearly mean. These trends were significant for light physical activity in winter (SMD = − 0.03, 95% CI − 0.58 to − 0.01, $P = 0.04$). Sleep appeared 64 min less during, compared to outside Ramadan (non significant). Narrative analyses for the impact of vacation and daylight savings suggested that light physical activity is higher during vacation and that sleep increases after the spring daylight savings transition, and decreases after the autumn transition.

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Conclusions: Research into temporal patterns in activity behaviours is scarce. Existing evidence suggests that seasonal changes and periodic changes to usual routine, such as observing religious events, may influence activity behaviours across the year. Further research measuring 24 h time use and exploring a wider variety of temporal factors is needed.

Keywords: Sleep, Sedentary behaviour, Physical activity, Systematic review, Temporal patterns, Seasonal, Vacation, Cultural patterns, Adults, Time use

Background

Insufficient sleep, excessive sedentary behaviour and insufficient physical activity are all common drivers of weight gain and obesity in adults [1, 2]. These suboptimal daily movement behaviours also increase the risk of many non-communicable diseases (i.e. coronary heart disease, high blood pressure, type 2 diabetes), all-cause mortality, certain cancers, anxiety, and depression [3–9]. Globally, it is estimated 27.5% of people are insufficiently active [10], and a third (32%) report high levels of sedentary behaviour (> 7 h a day) [11], resulting in a global economic burden in 2013 of INT $67.5 billion in health care expenditure and lost productivity [12]. A 2017 multi-country study found the percentage of people reporting insufficient sleep (< 7 h per night) [13] ranged from 26% (Canada) to 56% (Japan) [14].

Substantial resources are put into preventive health each year, including communicable disease control and health promotion (fostering healthy lifestyles, i.e. physical activity) [15]. Current health promotion campaigns typically intervene based on geography, demography (e.g. age or ethnicity) or socioeconomics (e.g. disadvantaged groups) [16–18], yet the timing of health promotion campaign delivery may be overlooked. Temporal factors such as season, cultural and festive periods, and vacation status may influence 24-h movement behaviours. Better understanding temporal patterns in adult movement behaviours may identify new health promotion campaign intervention targets.

Research exploring the temporal factors affecting movement behaviours is scarce. One previous systematic review ($n = 37$ studies) suggested that physical activity varied with season, being lower in winter and higher in summer [19]. However, this study was limited to physical activity only, and involved only narrative synthesis. No other reviews appear to explore temporal factors in movement behaviours. Consistent with contemporary approaches to viewing physical activity along with sedentary behaviour and sleep as forming the 24 h day, this review will consider the impact of temporal factors on all movement behaviours, and use a meta-analytic synthesis, to address the research question: What are the annual rhythms of daily movement behaviours (sleep, sedentary behaviour, light physical activity, and moderate-to-vigorous physical activity) in healthy adults, and what temporal factors appear to influence these?

Methods

Protocol and registration

This review follows PRISMA guidelines [20] and was registered on PROSPERO (ID CRD42020184012) [21].

Eligibility criteria

Studies were included if: they were cohort studies reporting objectively or subjectively measured minutes of sleep, sedentary behaviour, and/or physical activity (light and moderate-to-vigorous); participants were healthy adults aged 18 to 65 years (reflecting the typical age range of adults in health behaviour guidelines); the study explored a temporal pattern (e.g. seasonal effects, pre/post/during vacation or cultural festivals); and the study included at least two assessment time points within a 12-month period using a within-subject design (the most robust design for addressing our research question). Intervention and cross-sectional study designs were excluded along with studies exploring non-general population samples and studies conducted in controlled settings. Studies comparing weekdays to weekends were excluded if only one time point was measured, however longitudinal studies using this comparison were included and weekly means calculated. Studies with populations that spread outside the eligible age range were included if data were able to be extracted (or obtained from authors) for only those participants aged 18–65-years.

Information sources and search strategy

The search strategy was developed in consultation with an academic librarian. Six databases were searched in 2020; Embase, Medline, Ovid Emcare, Scopus, Sport Discus, and Web of Science. Temporal patterns included terms relating to seasons, holidays, vacations, and festivals. Specific terms relating to religious events were included for the three most commonly observed religions: Christianity, Islam and Hinduism [22]. Where possible, searches were limited to English language, humans, and adults 18–65 years of age. Athlete* or player* were

excluded terms and no limitation was placed on date range. Figure 1 shows the search strategy used for Medline.

Study selection

All studies were imported into EndNote (EndNote × 9, Clarivate, Philadelphia, USA) for duplicate removal. Remaining studies were exported to Covidence (Covidence systematic review software, Veritas Health Innovation, Melbourne, Australia) for screening. Two independent reviewers completed title and abstract and full-text screening, with a third reviewer consulted for disagreements.

Where necessary, authors of potentially eligible studies were emailed to request additional data. Reference lists of included studies were searched to identify additional studies.

Data collection

Two independent reviewers used a custom data extraction template, including: study design, exposure (e.g. season, vacation, cultural festival), participant characteristics (sample size, setting, age, sex), outcomes measured (sleep, sedentary behaviour and physical activity), tool used (e.g. accelerometry, questionnaire), assessment time points (duration and frequency), and results (means and standard deviations for daily minutes of each outcome).

Risk of bias in individual studies

Each study was appraised by two independent reviewers using the Joanna Briggs Institute (JBI) critical appraisal checklist for cohort studies [23]. Conflicts were resolved by a third reviewer. Three items (1, 2 and 6) were irrelevant to single-group study designs and were removed. Each item was rated "yes", "no", "unclear", or "not applicable". Studies were not excluded based on risk of bias results.

Data analysis

The primary outcome measure was mean daily minutes spent in sleep, sedentary behaviour, light physical activity and moderate-to-vigorous physical activity. Where moderate and vigorous physical activity were presented separately, the values were added. Where required, data was converted to be expressed as mean daily minutes. This involved combining groups where appropriate (e.g. combining males and females where reported separately), converting monthly data to seasonal data, and converting weekly data to daily data. Standard errors were converted to standard deviations. Where more than 10 studies are identified for an outcome, funnel plots will be used to examine publication bias [24].

Meta-analysis was conducted for outcome and exposures reported in multiple studies. For studies presenting seasonal data, an overall yearly mean (minutes per day) for each outcome was calculated to allow for comparisons with seasonal means. For studies exploring

Line	Search term	Result
1	Adult/	4910909
2	adult*.ti,ab,kw.	1211711
3	Exercise/	105807
4	(physical activit* or exercis*).ti,ab,kw.	372960
5	Sedentary Behavior/	8777
6	sedentary behavio?r*.ti,ab,kw.	6350
7	Sleep/	51468
8	sleep*.ti,ab,kw.	177205
9	Seasons/	104262
10	Holidays/	2853
11	(temporal pattern* or time pattern* or season* or holiday* or vacation* or festival*).ti,ab,kw.	169537
12	(Christmas or Thanksgiving or Easter or Ramadan or Diwali or Deepawali).ti,ab,kw.	3969
13	1 or 2	5647011
14	3 or 4 or 5 or 6 or 7 or 8	569167
15	9 or 10 or 11 or 12	220809
16	13 and 14 and 15	2500
17	limit 16 to (english language and humans)	2195
18	limit 17 to ("young adult (19 to 24 years)" or "adult (19 to 44 years)" or "middle age (45 to 64 years)")	2042
19	(athlete* or player*).ti,ab,kw.	99086
20	18 not 19	1618

Fig. 1 Medline database search terms

Ramadan, during-Ramadan data were compared with pre/post-Ramadan data. Where multiple data points were reported during or pre/post Ramadan, overall means were calculated by combining relevant data for each condition. A random-effects model was used to calculate standardised mean difference (SMD), pooled SMD, and associated confidence intervals (CI), along with forest plots generated using Review Manager (version 5.4, The Cochrane Collaboration). For seasonal data, estimates of the weighted mean difference (WMD) were calculated as the season mean minus the yearly mean expressed as minutes per day. Each calculation was performed by multiplying the overall yearly standard deviation by the SMD for the season of interest. Estimates of the WMD for during Ramadan compared with outside Ramadan was calculated by multiplying the overall standard deviation for outside-Ramadan by the SMD for during-Ramadan and expressed as minutes per day. Heterogeneity was assessed using the i^2 statistics, calculated using Review Manager. Analyses were performed in 2020.

Results

Included studies

The search identified 7009 results, including 4038 different studies, of which 3967 were deemed ineligible based on titles and abstracts. Of the 71 studies reviewed in full text, a further 54 studies were ineligible for several reasons, including 25 had an ineligible study design (e.g. experimental study or cross-sectional), 21 did not report an outcome of interest (minutes of activity), seven had an ineligible population (e.g. children, over 65 yrs., disease populations) and one full-text version of the study was unavailable after extensive searching. Seventeen studies, published between 2003 and 2019, were included (see Fig. 2). Two of the included studies became eligible as a result of contact with authors who provided additional data of interest [25, 26].

Study characteristics

Table 1 presents a summary of the included studies. Of the 17 included studies, four temporal exposures were present: seasonal patterns ($n = 11$) [26, 32–41], Ramadan ($n = 4$) [28–31] vacation ($n = 1$) [25], and daylight savings time transitions ($n = 1$) [27]. Studies were conducted across four continents: Europe, Africa, Asia, and North America. Most recruited participants from a single country, however, three studies included two or more countries [26, 38, 39]. Multiple studies were conducted in the USA ($n = 4$) [25, 32, 33, 40], Saudi Arabia ($n = 3$) [28–30], Sweden ($n = 2$) [37, 38] and England ($n = 2$) [34, 36], with single studies from Ghana [39], Norway [39], Denmark [38], Germany [35], Czech Republic [26], Slovakia [26], Poland [26], Japan [41], Italy [27], and Libya [31].

Participants

The studies involved a total of 1951 participants, with sample sizes ranging from 8 [30] to 960 [41], 14 had sample sizes less than $n = 100$. Mean participant age ranged from 18.1 years (SD = 0.3) [40] to 61.2 years (SD = 2.4) [26]. Most studies ($n = 12$) included mixed sex cohorts (range = 39 to 82% female), two had only female participants [32, 33], and three had only males [27, 30, 31].

Primary outcomes

Sleep was the most common activity examined ($n = 13$) [27–31, 34–41], with sedentary behaviour and light physical activity both measured in four studies [25, 26, 32, 34], and moderate physical activity and vigorous physical activity measured in five studies, either separately or combined as moderate-to-vigorous physical activity [25, 26, 32–34]. Ten studies used subjectively measured activity (i.e. survey, questionnaire, sleep diary) [25, 28, 29, 31, 33, 36, 37, 39–41], four studies used objective measures (accelerometry) [26, 27, 30, 32], and three studies used a combination (accelerometer and sleep diary) [34, 35, 38]. One study used a 24-h accelerometry protocol, allowing changes in sleep, sedentary behaviour, light physical activity and moderate-to-vigorous physical activity to be examined simultaneously [34]. Analyses were not performed to detect potential publication bias due insufficient studies for each outcome and subgroup analyses were not performed due to the limited data available.

Critical appraisal

Results from the JBI critical appraisal are presented in Table 2. Three studies received 'yes' responses for all items [26, 32, 34]. All studies measured the exposure in a valid and reliable way. Almost half of the studies did not identify confounding factors [25, 28–30, 33, 35, 37, 39], nine studies did not state strategies that were used to deal with confounding factors [25, 28–30, 33, 35, 37, 39, 40], whilst it was unclear for one study if strategies were used [31]. It was unclear whether Suzuki et al. [41] and Waterhouse et al. [31] measured outcomes in a valid and reliable way. More than half of the studies had incomplete follow-up [25, 28, 33, 36–41] whilst completeness of follow-up was unclear for one study [31]. Where follow-up was incomplete or unclear, most reported strategies used to address this, however it was unclear for the studies by Garde et al. [38] and Waterhouse et al. [31]. All studies were deemed to have used appropriate statistical analyses.

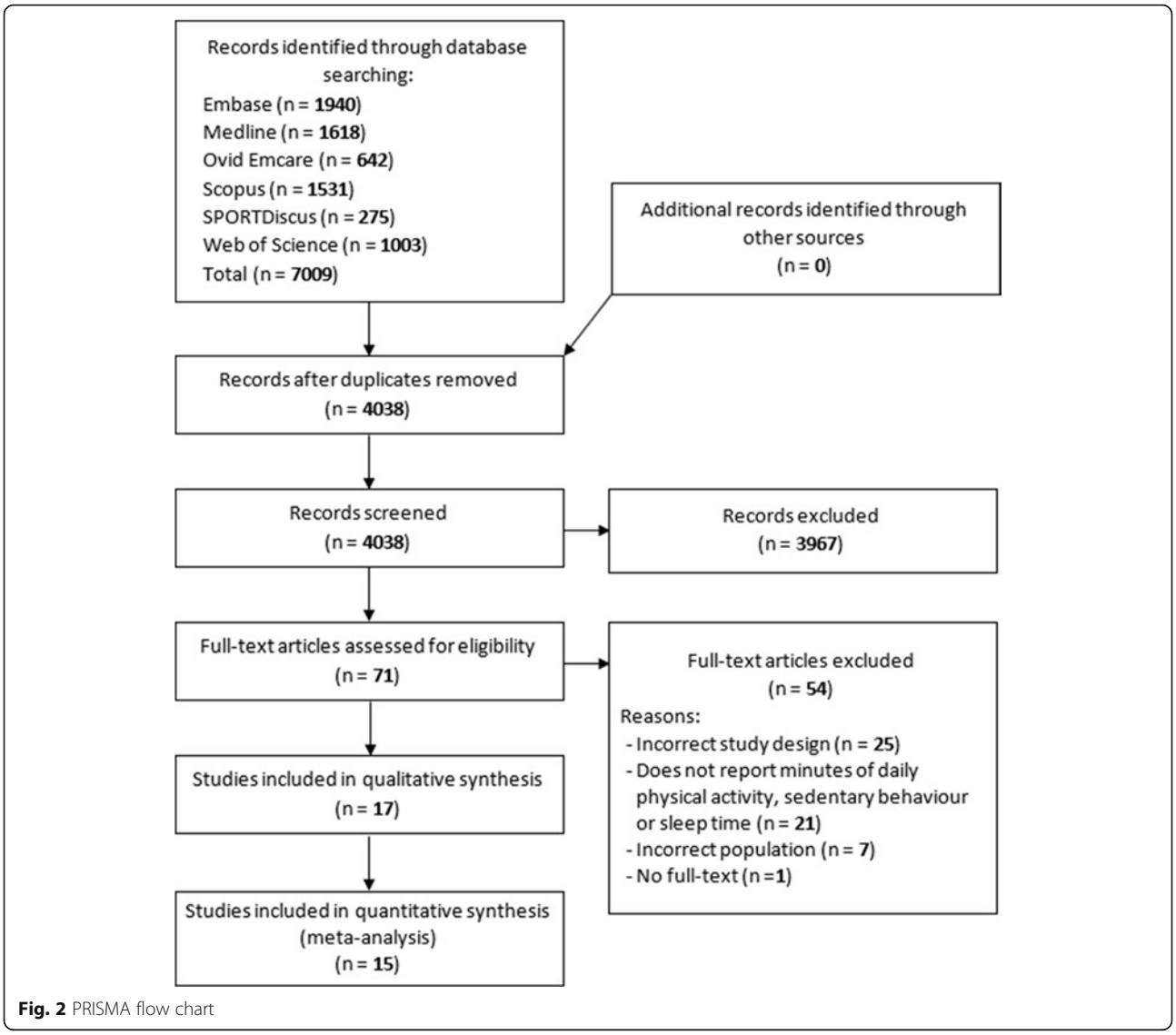


Fig. 2 PRISMA flow chart

Temporal factors

Season

Season was the most examined temporal factor, with 11 studies [26, 32–41].

Sleep (*n* = 8 studies) Eight studies reported sleep duration data across seasons (total participants *n* = 1587) [34–41]. Fig. 3 depicts forest plots for sleep in each season compared to the yearly average. Eight studies were included for winter and summer comparisons, and seven for spring and autumn comparisons. No season had significant differences compared to the yearly average. There was a trend towards higher daily minutes of sleep during winter (SMD = 0.05 [95% CI: − 0.02 to 0.12], WMD = 4 min/day) and autumn (SMD = 0.17 [95% CI: − 0.10 to 0.43], WMD = 12 min/day), and less during spring (SMD = − 0.21 [95% CI: − 0.51 to 0.10], WMD = − 15 min/day) and summer (SMD = − 0.06 [95% CI: − 0.13 to 0.01], WMD = − 4 min/day), when compared to the yearly mean. The largest change between seasons was an increase of 27 min/day from spring to autumn. Minimal heterogeneity between studies was observed for winter and summer (I^2 = 0%) and substantial heterogeneity was observed for spring and autumn (I^2 = 76 and 69% respectively).

Sedentary behaviour (*n* = 3 studies) Three studies reported sedentary behaviour data across seasons (total participants *n* = 153) [26, 32, 34]. Two studies were included in each comparison (Fig. 4). There were no significant differences in sedentary time in any season compared to the yearly mean. There was a trend towards higher daily minutes of sedentary behaviour during winter (SMD = 0.23 [95% CI: − 0.03 to 0.48], WMD = 19

Table 1 Summary of included studies ($n = 17$)

Study	Temporal pattern	Population	Age mean (SD), range, % female	Outcome	Tool	Assessment length, total, frequency
Tonetti 2013 [27]	Daylight savings time	University students, Italy ($n = 14$)	26.9 (3.3), 21 30, 0%	Sleep	Accelerometer: Actiwatch AW 64	7 days × 2, pre/post DST transition
BaHammam 2003 [28]	Ramadan	Fasting Muslim medical students, Saudi Arabia ($n = 56$)	22.6 (1.3), range NR, 45%	Sleep	Questionnaire[a]	5 weekdays ×4, pre/during Ramadan
BaHammam 2005 [29]	Ramadan	Healthy adults, Saudi Arabia (SF $n = 41$ & NSF $n = 30$)	SF: 32.6 (1.5), range NR, 39%. NSF: 29.3 (1.6), range NR, 44%	Sleep	Questionnaire[a]	5 weekdays × 3, pre/during Ramadan
BaHammam 2013 [30]	Ramadan	Male hospital staff, Saudi Arabia ($n = 8$)	36.3 (4.5), range NR, 0%	Sleep	Accelerometer: SenseWear Pro Armband	5 weekdays ×3, pre/during Ramadan
Waterhouse 2009 [31]	Ramadan	Healthy adults, Libya ($n = 20$)	Mean NR, range NR, 0%	Sleep	Questionnaire[a]	1 night × 4, pre/during/ post Ramadan
Buchowski 2009 [32]	Season (Wi, Su)	Healthy females, USA ($n = 57$)	36.5 (9.2), 20 54, 100%	SB, LPA, MVPA	Accelerometer: Tritrac R3D	7 days × 3, consecutive seasons
Pechova 2019 [26]	Season (Sp, Au)	Healthy adults, Czech Republic, Slovakia & Poland ($n = 50$)	61.2 (2.4), 55 65, % NR	SB, LPA, MPA, VPA,	Accelerometer: ActiGraph GT1M	8 days ×2, 6 month follow up
Lloyd 2013 [33]	Season (Wi, Sp, Su, Au)	Mexican American females, USA ($n = 36$)	33.9 (9.5), 20 63, 100%	MPA, VPA	Questionnaire: National Health and Nutrition Examination Survey	Prior 3 months ×5, quarterly
O'Connell 2014 [34]	Season (Wi, Sp, Su, Au)	Healthy adults, England ($n = 46$)	F: 42.7 (14.8), range NR. M: 39.5 (14.4), range NR, 72%	SB, LPA, MVPA, sleep	Sleep diary[a], accelerometer: ActiGraph GT1M	7 days × 4, consecutive seasons
Lehnkering 2007 [35]	Season (Sp, Au)	Medical students, Germany ($n = 34$)	Mean NR, 19 31, 56%	Sleep	Accelerometer: Actiwatch, Sleep diary[a]	15 days × 2, 6 month follow up
Shochat 2019 [36]	Season (Sp, Au)	University students, England ($n = 19$)	18.9 (0.8), range NR, % NR	Sleep	Sleep diary: Karolinska Sleep Diary	21 days × 2, 6 month follow up
Adamsson 2018 [37]	Season (Wi, Sp, Su, Au)	Daytime office workers, Sweden ($n = 30$)	F: 42.6 (10.0), 24 61, M: 45.2 (14.7), 21 64, 67%	Sleep	Sleep diary[a]	3 weekdays × 12, monthly
Garde 2014 [38]	Season (Wi, Sp, Su, Au)	Hospital staff, Sweden ($n = 22$) & research staff, Denmark ($n = 16$)	Sweden: 48.8 (9.2), 33 62, 73%. Denmark: 42.1 (9.8), 25 62, 63%	Sleep	Sleep diary: Karolinska Sleep Diary, accelerometer: Actiwatch AW4	1 workday night ×12, monthly
Friborg 2012 [39]	Season (Wi, Su)	University students, Ghana ($n = 200$) & Norway ($n = 200$)	Ghana F: 25.4 (7.5), 19 49, M: 25.3 (6.1), 19 51, 48%. Norway F: 22.7 (4.8), 19 50, M: 22.7 (5.5), 18 54, 73%	Sleep	Sleep diary[a]	7 days × 2, 6 month follow up
Ludy 2018 [40]	Season (Wi, Su)	University students, USA ($n = 60$)	18.1 (0.3), range NR, 82%	Sleep	Questionnaire: Youth Risk Behaviour Survey	7 days × 2, 4 month follow up
Suzuki 2019 [41]	Season (Wi, Su, Sp, Au)	Community residents, Japan ($n = 960$)	YA: mean NR, 19 31, % NR. MA: mean NR, 40 61, % NR	Sleep	Questionnaire[a]	14 nights × 4, consecutive seasons
Cooper 2016 [25]	Vacation	Healthy adults, USA ($n = 122$)	32.2 (13), range NR, 65%	SB, LPA, MPA, VPA	Questionnaire: International Physical Activity Questionnaire	7 days × 3, pre/during/ post vacation

Au autumn, *F* female, *LPA* light physical activity, *M* male, *MA* middle aged, *MPA* moderate physical activity, *MVPA* moderate to vigorous physical activity, *NR* not reported, *NSF* Non Saudi fasting group, *SB* sedentary behaviour, *SF* Saudi fasting group, *Sp* spring, *Su* summer, *VPA* vigorous physical activity, *Wi* winter, *YA* young adult

[a]tool purpose designed for study

Table 2 Joanna Br ggs nst tute cr t ca appra sa check st summary tab e

	Adamsson 2018 [37]	BaHammam 2003 [28]	BaHammam 2005 [29]	BaHammam 2013 [30]	Buchowski 2009 [32]	Cooper 2016 [25]	Friborg 2012 [39]	Garde 2014 [38]	Lehnkering 2007 [35]	Lloyd 2013 [33]	Ludy 2018 [40]	O'Connell 2014 [34]	Pechova 2019 [26]	Shochat 2019 [36]	Suzuki 2019 [41]	Tonetti 2013 [27]	Waterhouse 2009 [31]
Question	Responses																
3. Was the exposure measured in a va id and re iab e way?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
4. Were confounding factors identified?	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓
5. Were strategies to dea with confounding factors stated?	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✓	✓	✓	✓	✓	U
7. Were the outcomes measured in a va id and re iab e way?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	U	✓	U
8. Was the fo ow-up time reported and sufficient to be ong enough for outcomes to occur?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗
9. Was fo ow up comp ete, and if not, were the reasons to oss to fo ow up described and exp ored?	✗	✗	✓	✓	✓	✗	✗	✗	✓	✗	✗	✓	✓	✗	✗	✓	U
10. Were strategies to address incomp ete fo ow up uti ized?	✓	✓	✓	✓	✓	✓	✓	U	✓	✓	✓	✓	✓	✓	✓	✓	U
11. Was appropriate statistica ana ysis used?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Note – questions 1,2 and 6 omitted as not re evant to inc uded study design
✗ = no, ✓ = yes, U = unc ear

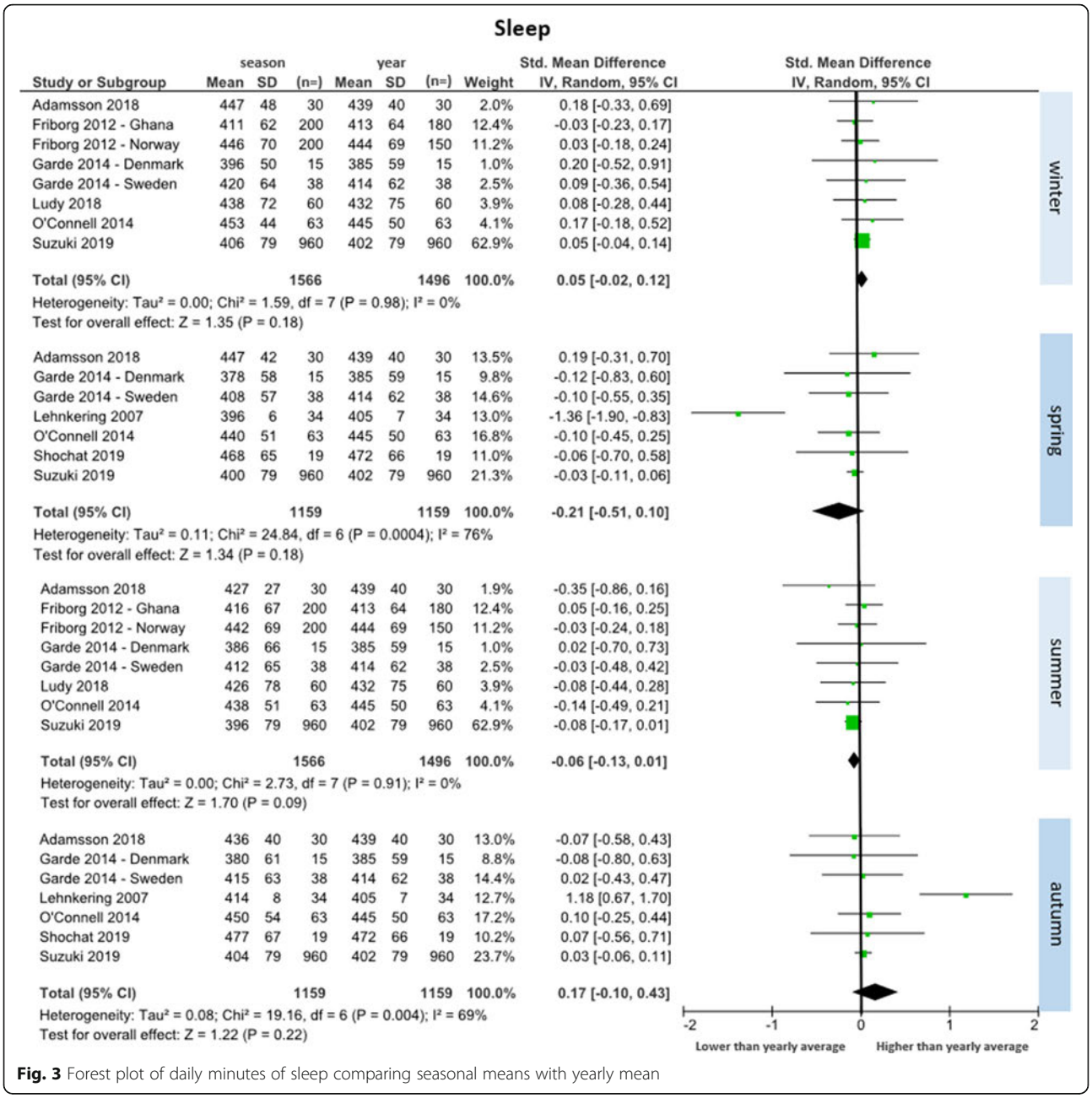


Fig. 3 Forest plot of daily minutes of sleep comparing seasonal means with yearly mean

min/day) and autumn (SMD = 0.11 [95% CI: − 0.15 to 0.37], WMD = 9 min/day), and less during spring (SMD = − 0.18 [95% CI: − 0.44 to 0.08], WMD = − 15 min/day) and summer (SMD = − 0.16 [95% CI: − 0.41 to 0.10], WMD = − 14 min/day), when compared to the yearly mean. The largest change between seasons was an increase of 36 min/day from spring to winter. Minimal heterogeneity between studies was observed across all seasons (I^2 = 0%).

Light physical activity (*n* = 3 studies) Three studies reported light physical activity data across seasons (total participants *n* = 153) [26, 32, 34]. Two studies were included in each comparison (Fig. 5). Significantly less light activity occurred during winter compared to the yearly mean (SMD = − 0.30 [95% CI: − 0.58 to − 0.01], WMD = − 26 min/day). No significant differences were found with the remaining seasons. There was a trend towards more light physical activity during spring (SMD = 0.20 [95% CI: − 0.06 to 0.46], WMD = 17 min/day) and summer (SMD = 0.22 [95% CI: − 0.03 to 0.48], WMD = 19 min/day), when compared to the yearly average, and less light physical activity in autumn (SMD = − 0.14 [95% CI: − 0.40 to 0.12], WMD = − 12 min/day). The largest

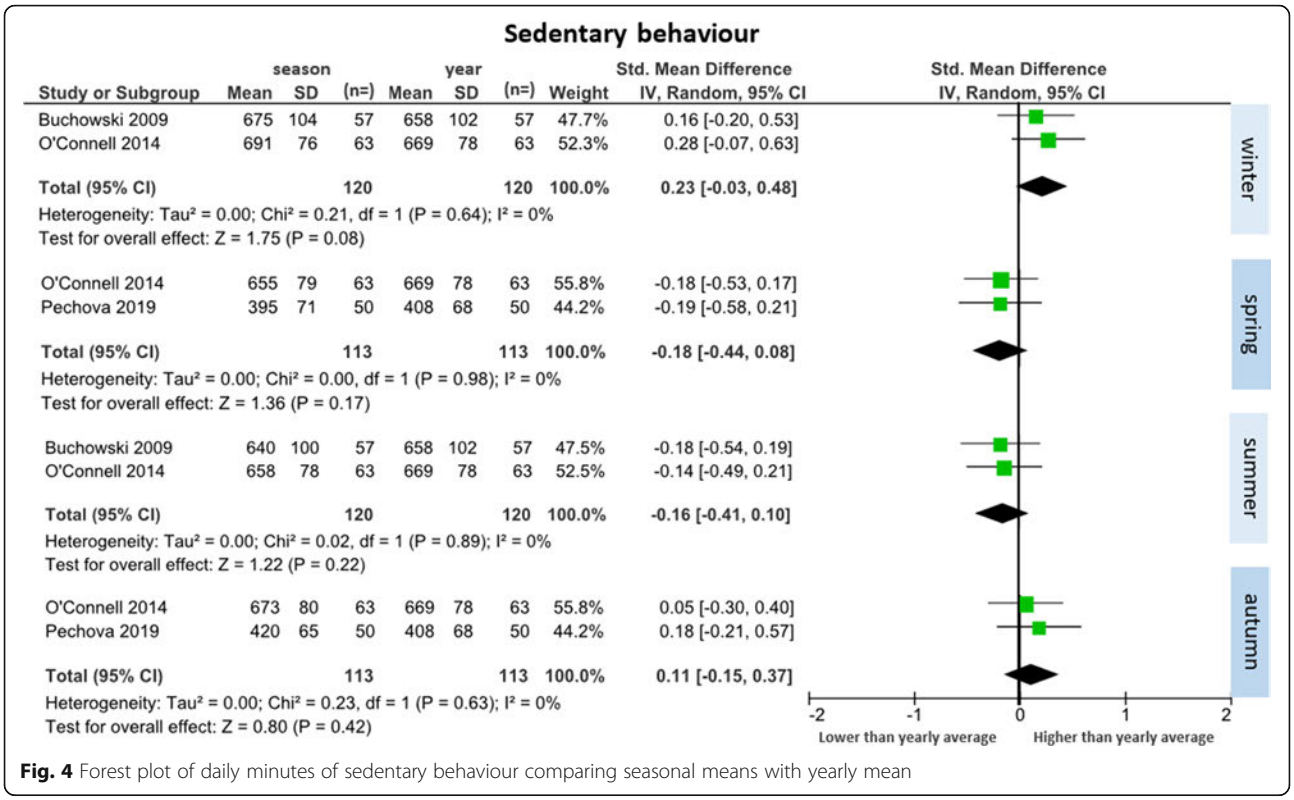


Fig. 4 Forest plot of daily minutes of sedentary behaviour comparing seasonal means with yearly mean

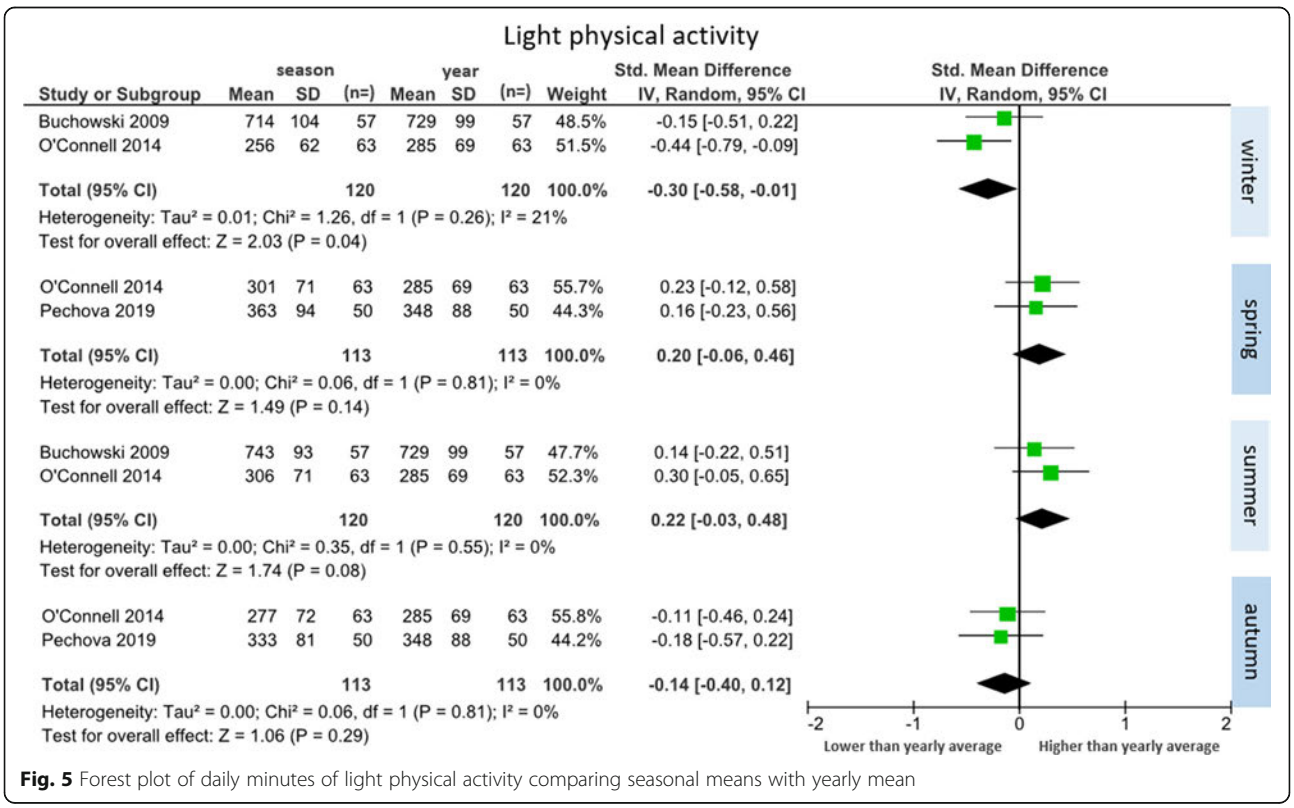


Fig. 5 Forest plot of daily minutes of light physical activity comparing seasonal means with yearly mean

change between seasons was an increase of 45 min/day from winter to summer. Minimal heterogeneity between studies was observed across all seasons (winter: I^2 = 21%; spring, summer and autumn: I^2 = 0%).

Moderate-to-vigorous physical activity (*n* = 4 studies)
Four studies reported moderate-to-vigorous physical activity data across seasons (total participants *n* = 189) [26, 32–34]. Three studies were included in each comparison (Fig. 6). There were no significant differences in any season compared to the yearly average. There was a trend toward less moderate-to-vigorous physical activity during winter (SMD = – 0.12 [95% CI: – 0.34 to 0.11], WMD = – 3 min/day) and autumn (SMD = – 0.06 [95% CI: – 0.28 to 0.17], WMD – 1 min per day). There was trend toward more moderate-to-vigorous physical activity during summer (SMD = 0.08 [95% CI: – 0.14 to 0.31], WMD = 2 min/day) and minimal difference from the yearly average for spring (SMD = 0.02[95% CI: – 0.20 to 0.25], WMD = 0.5 min/day). The largest change between seasons was an increase of 5 min/day from winter to summer. Minimal heterogeneity between studies was observed across all seasons (I^2 = 0%).

Ramadan (n = 4 studies)
Four studies explored daily activity patterns across Ramadan. All measured sleep duration only. For control, studies used either the week before Ramadan [28–30], or the mean of a night before and after Ramadan [31]. The overall SMD was non-significant when comparing sleep duration during Ramadan to pre/post Ramadan (SMD = – 0.47 [95% CI: – 1.05 to 0.10]). There was a trend towards less sleep during Ramadan than on the control nights (WMD = 64 min/day). Substantial heterogeneity was observed between studies (I^2 = 82%). See Fig. 7 for further detail.

Vacation (n = 1 study)
One study [25] explored the effect of vacationing away from home on sedentary behaviour, light physical activity and moderate-to-vigorous physical activity. Participants engaged in significantly more daily minutes of light physical activity on vacation than before (104 min [SD = 88 min] vs.71 min [SD = 74 min], $p < 0.001$)) and after vacation (104 min [SD = 88 min] vs. 68 min [SD = 73 min], $p < 0.001$)). This study reported a statistically non-significant trend for participants to have engaged in less daily minutes of sedentary behaviour (215 min [SD = 99

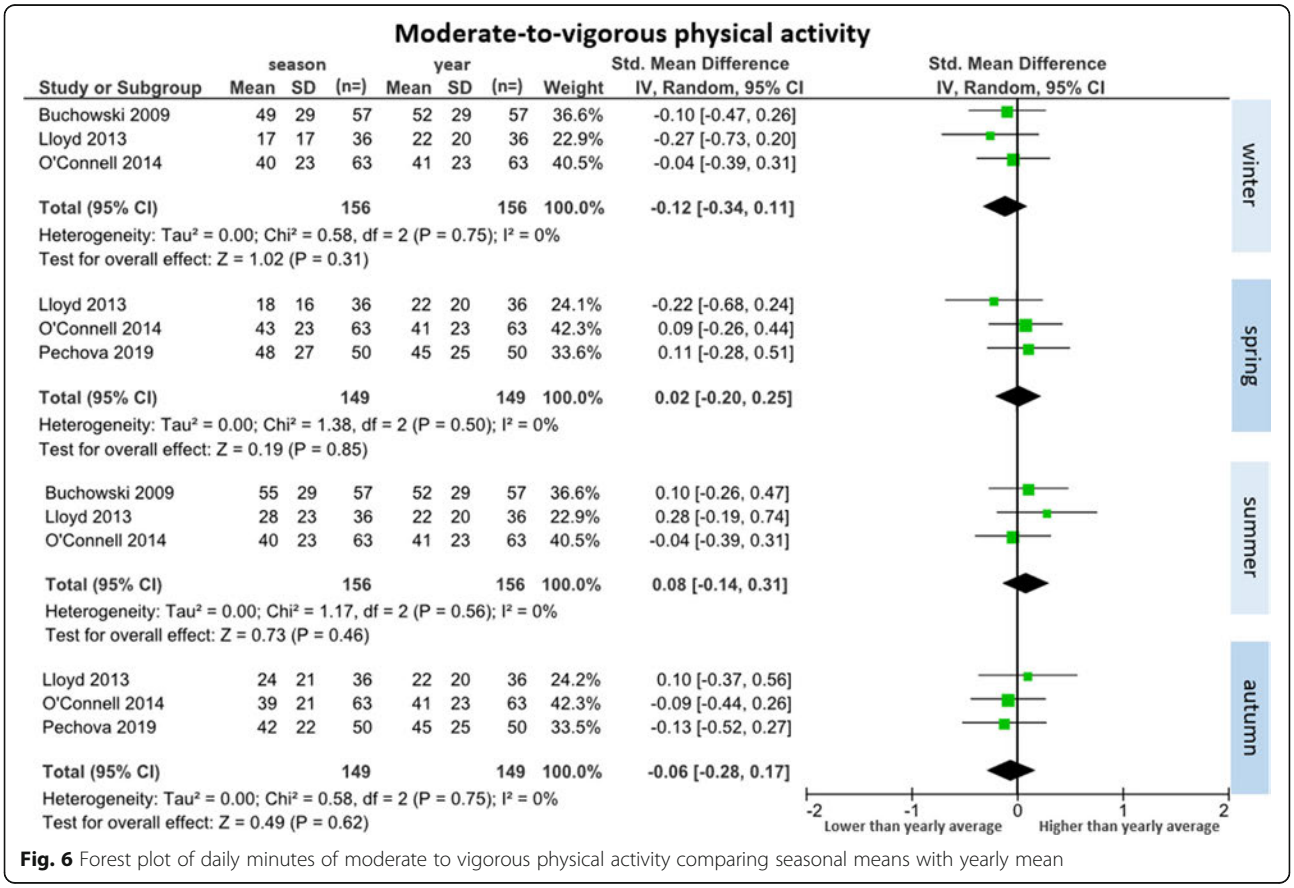


Fig. 6 Forest plot of daily minutes of moderate to vigorous physical activity comparing seasonal means with yearly mean

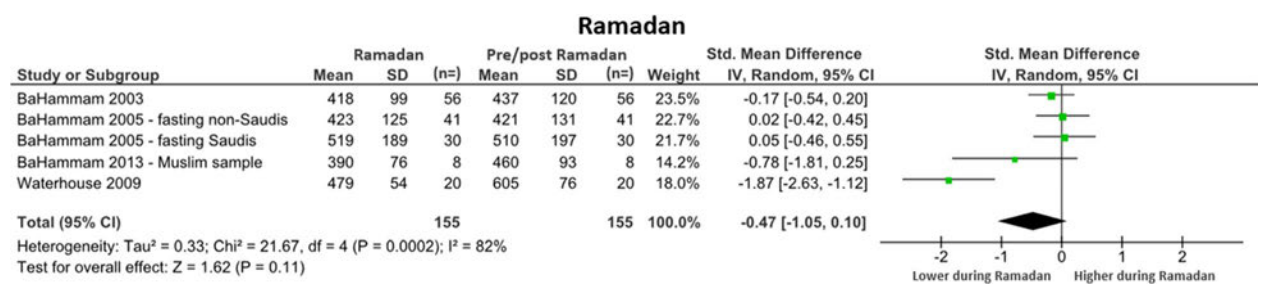


Fig. 7 Forest plot of daily minutes of sleep comparing during Ramadan with pre/post Ramadan

min]) compared with before (252 min [SD = 132 min]) and after vacation (251 min [SD = 131 min]), and a statistically non-significant trend to have engaged in less daily minutes of moderate-to-vigorous physical activity during vacation (29 min (SD = 35 min) compared to before (50 min [SD = 81 min]) and after vacation (41 min [SD = 46 min]).

Daylight savings time (n = 1 study)

One study [27] explored the impact of the change in daylight savings time on sleep, measuring sleep time at both the autumn transition out of daylight savings time and the spring transition into daylight savings time. In the week after the autumn transition out of daylight savings time, participants slept significantly less (25 min per day less, $p < 0.05$) than during daylight savings (365 min vs 340 min). In the week after the spring transition into daylight savings time, participants slept significantly more (28 min per day more, $p < 0.05$) than before daylight savings (340 min vs 368 min).

Discussion

Principal findings

This systematic review has brought together current evidence regarding annual rhythms in adults' daily movement behaviours and examined key temporal factors which may influence these rhythms. Results reveal only a handful of studies identified per temporal factor, mostly involving small sample sizes. Regardless, several trends emerged. Sleep appeared to be higher during autumn and winter, outside of Ramadan and after the transition into daylight savings time. Sedentary behaviour also appeared higher during autumn and winter, and during non-vacation periods. Light physical activity was higher during spring and summer and whilst on vacation, and moderate-to-vigorous physical activity appeared to be higher during spring and summer, and during non-vacation periods.

Seasonal effects on movement behaviours (particularly sleep) was the most commonly explored temporal factor. The meta-analyses were generally non-significant (except for light physical activity), however methodological factors may have contributed to this. Many studies used self-reported tools, which are known to have modest validity [42] and may in turn have limited the ability to accurately detect change over time. Secondly, study populations were small (especially for the sedentary behaviour, light physical activity and MVPA meta-analyses). However, the direction for change in movement behaviours across seasons were generally consistent across studies, and varied in the expected directions, suggesting that the non-significant trends may be real.

Results suggested sleep duration was approximately half-an-hour less in summer compared with autumn. This may influence health outcomes, particularly if sleep totals fall outside the optimal range for positive health outcomes of 7-8 h [43]. For example a one-hour decrease in sleep below 7 h is associated with a 6% increase in all-cause mortality, an 11% increase in cardiovascular disease risk [43], and a 9% increase in obesity risk [44]. Results suggested that sedentary behaviour is around 30 min higher in winter, relative to spring. It is questionable whether this would impact health. However, it was coupled with lower light physical activity (45 min less, relative to summer) and less moderate-to-vigorous physical activity (5 min less, relative to summer), which is likely to be of sufficient magnitude to have health consequences. For example, a 1 min per day increase in moderate-to-vigorous physical activity has been associated with a 2% decrease in all-cause mortality [45]. It has been suggested that as little as 15 min extra light physical activity, or 5 min extra moderate-to-vigorous physical activity, has a positive effect on all-cause mortality and cardiovascular disease [46].

It is important to consider that season interacts with climate and daylight hours differently in different geographic regions. Almost all seasonal studies included in this review took place in temperate climate locales in the mid-latitudes (between 23° and 66°) of the northern hemisphere. Temperate climates are characterised by mild-to-warm summers and cool-to-cold winters with moderate yearly rainfall [47]. Mid-latitudes have distinct differences in daylight hours between seasons of approximately 4-8 h between winter and summer. Only a single study sample originated in a tropical climate and latitude (Ghana) [39]. Given the small number of studies

in this review, it is not possible to disentangle the effects of season, climate and daylight hours. Temperate climates dominate the evidence presented here, and further research in tropical and subpolar regions is warranted.

Whilst this review sought studies examining various cultural, religious and festive periods', all eligible studies of this type related to Ramadan only, and its impacts on sleep. Ramadan is an example of a periodic change to typical lifestyle patterns. Specifically, Ramadan is a spiritual disciplinary practice, where people observing Ramadan do not eat or drink during daylight hours, changing usual mealtimes, along with usual bedtimes and wake times, and therefore changes in movement behaviours could be expected. Additionally, during this month, people are reportedly less active during daylight hours [48] however none of the included studies examined physical activity during Ramadan. Across studies, participants observing Ramadan generally went to bed and woke later, with the delay in bedtime more pronounced than wake-time. Whilst there was a trend towards less sleep during Ramadan, the weighted mean sleep duration of 7 h and 25 min falls within recommended levels of 7 or more hours per night [13]. It should be noted that Ramadan is the ninth month of the Islamic calendar, which is 10–12 days shorter than the Gregorian calendar, therefore over several years, Ramadan will occur across all seasons. It is possible the trends observed in sleep time across seasons may interact with Ramadan differently depending on the season, with shorter winter days allowing for an extended window to consume meals, impacting less on usual sleep times. Of the studies exploring Ramadan, three were conducted in Saudi Arabia, and one in Libya. Both countries are located at a similar latitude (approximately 16-33°), experiencing similar daylight hours across the year. Across the four included studies, Ramadan occurred between late Summer and mid-winter. While changes to sleep routine during Ramadan may be unaffected by seasonal changes at latitudes with small fluctuations in daylight hours across the year, future research in different locations is warranted.

The single study exploring daylight savings transitions reported a significant change in sleep duration of approximately half-an-hour after each transition, with less in autumn and more in spring. It is worth noting duration at all time points fell below recommended levels of sleep per night of 7 or more hours [13]. The immediate one-hour shift in clock time requires an adjustment period for our internal biological clocks to reset to the new timing of daylight hours, accounting for the immediate disruptions to sleep duration [49]. It is likely the observed changes in sleep duration return to pre-transition levels in following weeks, however further research for longer periods is needed to examine this. Further studies are needed before conclusions can be made about the impact of daylight savings transitions.

The final periodic temporal factor explored was vacation periods where again, only a single study was found. This study suggested participants on vacation got less moderate-to-vigorous physical activity and more light physical activity and sedentary time. Further research is needed to allow for the impact of vacations on movement behaviours to be understood. Additionally, future studies should explore movement behaviour intentions for vacation periods as it may be a risk factor for poor movement behaviour during vacation. The location or time of year when participants went on vacation was not reported, and thus it is important to consider that season may be a confounding factor.

Implications

This review identified trends towards negative changes in daily movement behaviours during several periods. Results suggest physical activity interventions may be needed during winter and autumn months where activity levels decline. Efforts could focus on alternate exercise options for these periods, such as indoor or home-based exercise routines, along with the provision of indoor or sheltered environments within the community to combat the environmental barriers during these colder, wetter and darker periods. Interventions promoting regular movement during winter and autumn could also target sedentary behaviour. Periodic temporal factors such as observing religious practices have potential to provide spiritual, physical and/or mental health benefits which would suggest these periods may not be the optimal time for movement behaviour intervention. Further research is needed to understand whether there are significant and lasting effects on usual movement behaviours resulting from periodic temporal factors. Opportunities may exist to promote pre-emptive behaviour changes, to counteract the effects of these periodic temporal factors if those effects are found to be impactful on health. For example, increased physical activity could be encouraged in the lead up to vacation or moving bedtime earlier before the autumn daylight savings transition.

Strengths and limitations

This is the first systematic review and meta-analysis of its kind. Several strengths to this systematic review include:, the search strategy was rigorous and designed in consultation with an academic librarian, and followed PRISMA guidelines [20]; study screening, data extraction and risk of bias were all performed in duplicate, increasing accuracy and trustworthiness of results.

A key limitation of the review was the relatively small number of studies exploring each of the four included temporal factors, ranging from one study each for

daylight savings time and vacation, to 11 studies for season. Most studies had small sample sizes ($n = 60$ or less in 14 studies). The sleep meta-analyses were dominated by a single study with a comparatively large sample ($n = 960$). Only one of the included studies reported the 24-h day, with a large portion of studies measuring sleep only. Limiting to English language studies may have reduced the variety of temporal patterns explored, specifically cultural or religious events in non-English speaking countries. Only a limited number of countries were included, each with their own seasonal and daylight hour patterns, therefore findings may not be representative of countries not explored in this review.

Future recommendations

This systematic review highlights the limited number of cohort studies exploring annual patterns of activity. Future research with larger sample sizes, in more diverse geographic areas, and using high quality movement behaviour measurement methods, are needed. Very little research has examined changes in daily movement behaviours during festive and cultural periods. Additionally, no studies have explored the interaction between temporal factors. Changes in a particular behaviour must be necessarily compensated by a change in another behaviour, given that there are 24 h in a day. Methodologies which measure multiple movement behaviours simultaneously, ideally using a 24-h measurement approach, are needed.

Conclusions

This study examined current research exploring annual rhythms in adults' daily movement behaviours and the key temporal factors which may influence these rhythms. Several trends were observed across each temporal factor including more sleep in autumn, winter and outside Ramadan, more sedentary behaviour in autumn and winter, and more light physical activity and moderate-to-vigorous physical activity in spring and summer. These trends highlight potential at-risk periods of negative movement behaviours (decline in sleep and physical activity, increase in sedentary behaviour) which may inform the timing and aid the design of health promotion and interventions strategies. Only single studies for daylight saving transitions and vacation were included, making it difficult to draw conclusions on the impact of these temporal factors. The current evidence for temporal patterns of movement behaviours and the association with temporal factors is scarce. Future research should aim to explore the 24-h day of movement behaviours using larger samples from a greater diversity of geographic areas, along with exploring a wider variety of temproal factors that may influence these behaviours.

Abbreviations

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta Analyses; SMD: Standardised mean difference; WMD: Weighted mean difference

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Authors' contributions

T.F., C.M., R.C. and F.F. were responsible for study inception and design. T.F. conducted all database searches. T.F., C.N., R.L. and R.V. were responsible for screening of articles, data extraction and quality assessment. R.C. acted as a third independent reviewer for resolving conflicts in screening and quality assessment. T.F. was responsible for data transformation. T.F. and C.M. were responsible for meta analysis of the data. T.F. led manuscript writing while C.M., R.C. and F.F. provided substantive feedback. All authors read and ap proved the final manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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STUDY PROTOCOL Open Access

Annual rhythms in adults' lifestyle and health (ARIA): protocol for a 12-month longitudinal study examining temporal patterns in weight, activity, diet, and wellbeing in Australian adults

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Abstract

Background: Almost one in three Australian adults are now obese, and the rate continues to rise. The causes of obesity are multifaceted and include environmental, cultural and lifestyle factors. Emerging evidence suggests there may be temporal patterns in weight gain related, for example, to season and major festivals such as Christmas, potentially due to changes in diet, daily activity patterns or both. The aim of this study is to track the annual rhythm in body weight, 24 h activity patterns, dietary patterns, and wellbeing in a cohort of Australian adults. In addition, through data linkage with a concurrent children's cohort study, we aim to examine whether changes in children's body mass index, activity and diet are related to those of their parents.

Methods: A community based sample of 375 parents aged 18 to 65 years old, residing in or near Adelaide, Australia, and who have access to a Bluetooth enabled mobile device or a computer and home internet, will be recruited. Across a full year, daily activities (minutes of moderate to vigorous physical activity, light physical activity, sedentary behaviour and sleep) will be measured using wrist worn accelerometry (Fitbit Charge 3). Body weight will be measured daily using Fitbit wifi scales. Self reported dietary intake (Dietary Questionnaire for Epidemiological Studies V3.2), and psychological wellbeing (WHOQOL BREF and DASS 21) will be assessed eight times throughout the 12 month period. Annual patterns in weight will be examined using Lowess curves. Associations between changes in weight and changes in activity and diet compositions will be examined using repeated measures multi level models. The associations between parent's and children's weight, activity and diet will be investigated using multi level models.

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Discussion: Temporal factors, such as day type (weekday or weekend day), cultural celebrations and season, may play a key role in weight gain. The aim is to identify critical opportunities for intervention to assist the prevention of weight gain. Family based interventions may be an important intervention strategy.

Trial registration: Australia New Zealand Clinical Trials Registry, identifier ACTRN12619001430123. Prospectively registered on 16 October 2019.

Keywords: Physical activity, Sedentary behaviour, Sleep, Diet, Weight, Overweight, Obesity, Epidemiology, Compositional data

Background

Australian obesity rates are amongst the highest in the world. Almost one in three Australian adults are obese (31%), and a further third are overweight (36%) [1]. Out of the 34 OECD countries, Australia's adult obesity rate ranks 5th highest, and has shown large increases over the past 10 years, in contrast to counties that are reporting modest growth (Canada and Spain) or even stabilisation (US and UK) [2]. Excess weight, and obesity in particular, is a major risk factor for numerous health conditions including cardiovascular disease, type 2 diabetes, some musculoskeletal conditions and some cancers [3–5]. In 2017, the total annual cost of obesity in Australia was estimated at $11.8 billion [6]. Fully understanding the mechanisms underpinning obesity is crucial if targeted and effective obesity programs are to be developed.

The determinants of obesity are complex. Ecological models recognise they include individual, social, and environmental factors. In particular, excess energy intake through unhealthy eating patterns, insufficient energy expenditure due to lack of physical activity and excess sedentary behaviour, and unhealthy sleep, have been highlighted as key modifiable individual risk factors [7, 8]. Such risk factors are socially and geographically patterned and tend to cluster within individuals and families. In particular, people with lower socioeconomic status are more likely to be overweight or obese, this gap is wider in women, and people in regional areas are more likely to be overweight or obese [9]. Family factors, such as meal-time patterns, parenting style and work patterns have also been show to influence childhood obesity [10]. While we recognise that these determinants have genetic, social and geographical origins, less attention has been paid to temporal patterning.

Weight gain across the year

Longitudinal studies suggest that, on average, Australian adults aged less than 65 years gain around 0.5 kg [11] and 0.6 cm of waist girth [11, 12] per year. However, the temporal patterning of this weight gain across the year is poorly understood. Research suggests that both weekly and annual cycles in day type (weekday and weekend days), cultural events, and season intertwine to influence adults' weight gain, activity patterns and eating patterns across the year, as outlined below.

Studies of days of the week suggest health behaviours may differ between weekdays and weekend days. For example, a US study of 9000 adults found that energy intake was 6% higher on weekend days compared to weekdays, with increased proportions of energy from fat and alcohol on weekends [13]. In addition, studies have suggested physical activity is lower on weekend days than weekdays [14, 15], while sleep duration is longer on weekend days [16, 17].

Studies of festive periods, and particularly the "holiday season" (in the West, from around late November through to early January, taking in Thanksgiving, Christmas and New Year's Eve) show that weight gain coincides with cultural celebrations. US "holiday season" weight gain is consistently 0.4–0.9 kg [18], and it appears that average weight gain over this 6-week period may account for the majority of annual weight gain [19]. A study of weight change in three Northern Hemisphere countries (US, Germany and Japan) found that weight gain coincided with cultural celebrations, however the relative importance of celebrations for weight gain varied between countries – in particular, the percentage weight gain at Christmas and Easter in Germany was almost double that for the US, and in Japan, most weight gain occurred during the May "Golden Week" celebration [20].

Studies of seasonal changes in weight and health behaviour suggest weight peaks in winter and troughs in summer [21]. Seasonal differences in energy and nutrient intake have been reported, though they are generally small in magnitude, and the direction of such differences is inconsistent between studies [13, 22]. Similarly, some studies have shown that adults sleep more in winter [23, 24], while others have shown no seasonal difference in sleep [25, 26]. Adult studies in the US and Europe found that people are relatively more active in summer than in winter [27–29]. However, a recent study of children suggests different patterns may occur in Australia and Canada– while Canadian children were relatively more active in summer than winter, the opposite was seen for Australian children [30]. The authors suggested that this

may be a product of Australia's winters being relatively mild compared with Canada's, and Australia's summers being relatively harsher.

In sum, the evidence suggests that temporal patterning in activity and diet across the year leads to cyclical spikes in weight gain, which accrue over time. However, research to date has been piecemeal, focussed on only diet, or activity patterns or weight gain, and not all three simultaneously. Additionally, Australian data are lacking; it is possible that international findings may not reflect Australian patterns, due to key differences in timing of festivities by season (e.g. Australian Christmas falls in summer) and climate (e.g. Australian winters are relatively mild and summers relatively harsh). Finally, most research on the effects of daily physical activity, sedentary behaviour and sleep has examined the activities in isolation and applied standard multivariate statistical techniques which assume that daily activities are independent. However, activity data are naturally co-dependent – they occur in a finite 24-h window, thus if one activity increases (e.g. moderate to vigorous physical activity), then another must decrease (e.g. sleep). Research employing frequent waves of data collection, taking into account the compositional nature of activity data, is required to understand temporal patterns of weight gain, activity and dietary intake in order to enable the design and implementation of interventions at the time they are needed most. For example, if most annual weight gain occurs at Christmas, and this coincides with unhealthy eating patterns, dietary interventions could be targeted in the lead up to Christmas. This aims of this study are therefore to:

1. Describe the annual rhythms in adults' body weight, daily activities and eating patterns, and determine whether changes in body weight across the year are associated with changes in activity and diet compositions.
2. Determine whether changes in children's body mass, activity and diet compositions are related to those of their parents, and
3. Examine whether parental factors (parenting style and home environment) are associated with changes in children's body mass, activity and diet compositions.

Methods

Study design

This is a prospective cohort study "Annual Rhythms In Adults' lifestyle and health" (ARIA) that will measure weight, daily activity, dietary intake, and wellbeing over a 12 month period. The study has been approved by the University of South Australia Human Research Ethics committee (Protocol number: 201901) and registered on the Australian New Zealand Clinical Trial Registry (Trial ID: ACTRN12619001430123). The South Australian Department for Education and Catholic Education South Australia has provided approval to match ARIA data with data from children in a concurrent cohort study, the "Life on Holidays" study [31], as further described below.

Participants and procedure

A community-based sample of 375 predominantly middle-aged adults will be recruited from the greater metropolitan area of Adelaide, South Australia, using two methods. Firstly, all parents and guardians of children enrolled in a separate three-year cohort study, "Life on Holidays" [31], will be invited to participate via email or postal invitation. In the Life on Holidays study, 380 children were recruited from Adelaide metropolitan schools in two waves commencing Feb 2019 and Feb 2020. Schools were randomly selected and invited from low, middle and high socio-educational advantage tertiles to ensure a representative sample. Anticipating the uptake from these parents to be a challenge, given the burden of participating in simultaneous 12-month trials, a second recruitment method is planned in case it is needed. Parents meeting the inclusion criteria will also be recruited through general advertising (social media posts, paid Facebook advertisements, print media). Mirroring the Life on Holidays protocol, participants will be enrolled in two waves (December 2019 and December 2020). Inclusion criteria are parent/guardian of a child enrolled in Life on Holidays or parent/guardian of child aged 5 to 12 years, 18 to 65 years old, residing in greater metropolitan Adelaide, with access to a Bluetooth-enabled mobile device or computer and home internet, proficiency in English, and ambulant. Exclusion criteria are pregnancy, having an implanted electronic medical device, or experiencing or receiving treatment for any life-threatening condition which impacts daily lifestyle and health.

Participants will comprise two cohorts: those beginning in December 2019 and those beginning in December 2020. A baseline face-to-face home visit will be conducted between August and November in the year of commencement, where participants will have their height measured and be given a Fitbit Charge 3 activity monitor and Fitbit Aria body weight scale (Aria 2 or Aria Air scale; Fitbit Inc., San Francisco, CA, USA). Participants will be asked to wear the activity monitor continuously except during water-based activities, and to weigh themselves daily. To enable remote collection of daily activity and weight data, participants will authorise bespoke software, "Fitnesslink", to access their Fitbit user account data, including user profile details, sleep, activity

and weight data, and device data (battery status and time of most recent sync).

Participants will complete a baseline survey about their demographic, health, and lifestyle characteristics either before or during the home visit. They will also complete eight online surveys about recreational physical activity, dietary intake, psychological wellbeing, weight perception/management, and work/holiday status over 12 months (see Fig. 1). Four of the online surveys are scheduled to coincide with assessments conducted in the Life on Holidays study to allow for within-family comparisons.

Upon completion of the study, participants will be provided an honorarium of $100 and will be allowed to keep the Fitbit Charge 3 and weight scales.

Measures

Body weight

Body weight will be measured using Fitbit Aria electronic weight scales (Fitbit Inc., San Francisco, CA, USA) [32, 33]. Participants will be encouraged to weigh themselves preferably daily but at least weekly, in the morning, whilst wearing minimal clothing, prior to meals and after voiding. Participants who do not wish to weigh in the morning will be asked to weigh at the same time on each occasion. Body weight data will be uploaded to participants' Fitbit accounts and collected remotely via the Fitnesslink software. Height will be measured at baseline home visit using a stadiometer (Leicester Height Measure MKII). Measures will be conducted according to International Society for the Advancement of Kinanthropometry assessment procedures [34].

Daily activity composition

Daily activity composition will be measured continuously using Fitbit Charge 3 activity monitors (Fitbit Inc., San Francisco, CA, USA). Participants will be asked to wear the device on their non-dominant wrist 24-h a day, except during water activities and device charging, and to sync data to their Fitbit account at least every 5 days. Data will be collected remotely via the Fitnesslink software, created especially for this study. Each minute in every 24-h period will be classified as sleep, sedentary, light, moderate or vigorous physical activity according to Fitbit's proprietary algorithm, which also provides bedtime and rise time. Minutes classified as sedentary (recorded when no other activities are detected) AND with missing heart rate data will be classified as non-wear. Fitbit activity monitors are commonly used in biomedical research [35, 36] and have acceptable validity for moderate-to-vigorous physical activity (Fitbit Flex compared to Actigraph GT3X+ $r = 0.731$ [37]), sleep (Fitbit Charge 2 compared to polysomnography sensitivity = 0.96, specificity = 0.61 [38]; Fitbit Flex compared to polysomnography $r = 0.97$ [39]) and total daily energy expenditure (Fitbit Flex compared to doubly labelled water in free-living conditions $r_s = 0.84$ [40]).

Recreational activity.

Recreational physical activity will be assessed at each timepoint using items from the How Areas in Brisbane Influence Health and Activity (HABITAT) study [41] which will be modified to reflect recreational activity over the previous month. Participants rate how often they did 15 activities (e.g. running or jogging, team sports, water activities) on a 5-point scale (never, once a month, once every 2 weeks, once a week, more than once a week). Participants will also report the number of hours they watch television or use an electronic device (computer, tablet, smartphone, video games) in their free time (1) on typical a weekday and (2) on typical a weekend day.

Dietary intake

Dietary intake will be assessed at each timepoint using the online Dietary Questionnaire for Epidemiological Studies (DQES v3.2; Cancer Council Victoria) [42], which will be modified to reflect diet over the previous month. The DQES v3.2 is an online self-administered

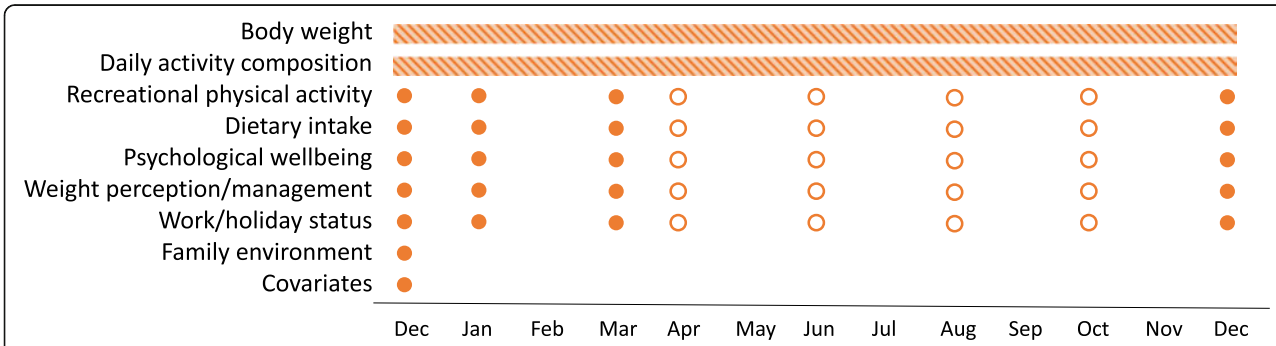


Fig. 1 ARIA assessment schedule. Bars indicate continuous assessment. Full dots indicate assessments coinciding with Life on Holidays assessments. Empty dots indicate assessments at additional timepoints

questionnaire that estimates nutritional intake (grams of foods, macro nutrients and micronutrients) based on 144 foods and beverages using nutritional information from the NUTTAB 2010 [43] and AUSNUT 2007 [44]. The DQES has been demonstrated to have good reproducibility and has good agreement with weighed food records [45, 46].

Psychological wellbeing

Quality of life will be assessed at each timepoint using the World Health Organization Quality of Life assessment 26-item version (WHOQOL-BREF) [47]. WHOQOL-BREF is a self-report questionnaire which measures four broad domains: physical health, psychological health, social relationships and environment. The WHOQOL-BREF has good discriminant validity, content validity, test-retest reliability and internal consistency [47–49]. The online version of the questionnaire is a valid and reliable alternative to the original paper-based version of the questionnaire [50].

Symptoms of depression, anxiety and stress will be assessed at each timepoint using the 21-item short-form Depression Anxiety Stress Scale (DASS-21) [51]. Participants rate the extent to which they agree with 21 statements such as "I found it hard to wind down" on a 5-point scale from 1 "Did not apply to me at all" to 5 "Applied to me very much, or most of the time". The DASS-21 has good convergent and discriminant validity when compared with other validated depression and anxiety measures, adequate construct validity, and high reliability [51–53].

Weight perception and management

At baseline, participants will report whether they consider themselves to be an acceptable weight, underweight or overweight and whether they have been weight stable (within 5% of body weight) in the past 3 months [54]. At each timepoint, participants will report whether they have used a range of weight control practices in the past month (adapted from the Behavioral Risk Factor Surveillance System [55]) and whether they currently use any medication from a list of six broad categories that can be associated with weight change [56, 57].

Work/holiday status

At baseline, participants will report their occupation (open-ended response), whether they work shift work that includes some night shifts, and whether they regularly work on weekends. At each time point, participants will report their average hours of work outside the home (none, less than 15 h per week, 15 to 30 h per week, full-time 36h hours per week), whether (and on what days) they have been on holidays or had annual leave since the last assessment (in the previous month at baseline), and whether (and on what days) they were away from home during that time.

Family environment

A range of family environment measures will be completed at baseline. Parenting style will be measured using the parenting warmth and parenting consistency scales from the Longitudinal Study of Australian Children [58]. Participants will report how they encourage their child's physical activity on a 4-item scale adapted from adapted from ISCOLE Neighborhood and Home Environment Questionnaire [59] and describe how meals take place on the "Structure of Family Meals" subscale of the Meals in Our Household Questionnaire [60]. Participants will also report whether a TV, computer or video game system (non-hand held; PlayStation, Xbox, etc.) are in their bedroom and their child's bedroom (adapted from ISCOLE [59]).

Baseline covariates

At baseline, participants will report their date of birth, sex, country of birth, marital status (never married, widowed, divorced, separated but not divorced, married or de facto), number of adults and number of children at home. Socioeconomic status measures include highest education level (below year 10, year 10, year 11, year 12 or equivalent, certificate III/IV, advanced diploma/diploma, bachelor degree, postgraduate or higher degree), combined gross household income (<$50,000, $50,000–$99,999, $100,000–$199,999, ≥$200,000), number of motorised vehicles in the household, and type of television/streaming service. Participants will report their smoking status and whether they have any of ten listed chronic conditions (adapted from the Australian National Health Survey [1]). Participants will also report their sleep chronotype (single item from both the Horne-Östberg Morningness-Eveningness-Questionnaire [61]) and complete an 8-item scale assessing their tendency towards routine [62].

Power calculation

Due to the complex nature of the multilevel model addressing Aim 1, current sample size software is unable to estimate the required sample size. We have therefore calculated the required sample size for a multivariable linear regression model, using conservative estimates, with added adjustments for clustering within families. For the initial estimate, a sample size of 226 achieves 90% power to detect an r^2 of 0.10 attributed to 10 independent variables when the significance level (alpha) is 0.025. In addition, data are clustered within families, with an expected average cluster size of 1.5, and an ICC of 0.7. This equates to a design effect of 1.35, bringing

the required total to 305 subjects. Allowing for 20% withdrawals/loss to follow up, the final sample size is 371. These estimates are approximate, but suggest that the anticipated sample size of 375 will provide sufficient power.

Statistical analysis

Longitudinal compositional data analysis methods will be used to assess activity and diet compositions. To account for the inherent co-dependency of compositional parts (proportions of time or macronutrients), compositions will be expressed as sets of isometric log ratios (ilrs) before their inclusion in statistical models [63, 64]. Aim 1 will use data from all participants. Aims 2 and 3 will use data only from parents/guardian of children enrolled in Life on Holidays and matched data from children in Life on Holidays.

Aim 1

Annual rhythms will be described graphically using Loess curves. Associations between change in weight (dependent variable) and changes in activity and diet compositions (independent variables) will be examined using multilevel modelling to adjust for non-independence of data, allowing for nesting of repeated measures within individuals and individuals within families. Diet and activity will be examined simultaneously to identify unique effects on weight. Covariates will include age, sex, socioeconomic status, and total energy intake.

Aim 2

Associations between change in children's (dependant variables) and parents' (independent variables) weight, activity, and diet compositions will be examined using a series of multilevel models to adjust for non-independence of data. Covariates will include parental and child age, sex, socioeconomic status, and child total energy intake.

Aim 3

Factor analysis will be used to derive factors from the baseline family environment items. The association between change in children's body mass index z-score, and activity and diet compositions (dependant variables) and family environment (independent variable) will be examined using a series of multilevel models. Covariates will include parental and child age, sex, socioeconomic status, and total energy intake.

Discussion

A main strength of this study is its novelty — it will be the first in the world to simultaneously examine temporal patterns in weight, daily activities and diet. Additional strengths are the use of wireless tracker technology and wifi scales to provide high fidelity information about adults' activity patterns and weight changes across the full year, with low participant burden. The study will use a compositional analysis approach, which is quickly gaining traction in time-use epidemiology. In addition, the opportunity to link parents' and children's data will allow examination of the interplay between temporal and family determinants of obesity.

Potential limitations must also be acknowledged. The study only targets adults who are parents. While the majority of Australian adults are parents (approximately 75% of 45–49 year old Australian women have children [65]), we acknowledge that their data may not represent adults who are not parents, or likewise those who are not motivated to participate in a research study. In addition, participants are recruited from a single Australian city (Adelaide, population 1.3 million); however, surrounding areas are included so that participants are drawn from metropolitan, suburban areas, and rural areas. It is possible that the weighing regimen may cause reactivity, given that frequent self-weighing can be an effective weight intervention strategy [66]. Reactivity will be reduced by allowing weekly weighing (i.e. not enforcing daily weighing), explaining to participants that the purpose of the study is to monitor usual lifestyle (not intervene), and through use of automated data collection (preventing the need for journaling).

With nearly one-third of Australian adults obese, a further one-third overweight, and rates continuing to rise, obesity is one of the greatest health challenges facing Australia. To date, public health obesity campaigns have typically intervened by geography (e.g. rural and remote), demography (e.g. targeted ethnic groups) or socioeconomically (e.g. low SES families). However, it appears likely that temporal factors, such as day type, cultural celebrations and season, may also play a key role in weight gain. It is hoped that this study's findings will reveal critical moments for intervention to assist the prevention of weight gain.

Furthermore, the study will examine the interplay between temporal and family determinants of obesity. If our results reveal intergenerational concordance in temporal patterns of weight gain, activity and diet compositions, this would suggest that carefully-timed, family-based interventions could be an important intervention strategy. Recent research suggests that parent-child obesity interventions may be a particularly effective [67], yet under-used, intervention strategy.

Abbreviations

DASS 21: Depression Anxiety Stress Scale; DQES: Dietary Questionnaire for Epidemiological Studies; Ilrs: Isometric log ratios; WHOQOL BREF: World Health Organization Quality of Life assessment 26 item version

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Authors' contributions
CAM and TO conceptualised the project. CAM, TO, FF, GAH, DD, RGC, AE and WJB obtained the funding. All authors provided input into the study design. RGC and CAM drafted the manuscript. All authors have critically evaluated the manuscript for content and approved the final version.

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Availability of data and materials
N/A

Ethics approval and consent to participate
Ethical approval has been attained from the University of South Australia Human Research Ethics Committee, Adelaide, Australia (201901). Participants will provide informed written consent.

Consent for publication
N/A

Competing interests
The authors declare that they have no competing interests.

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Rachel Curtis

From: no_reply@unisa.edu.au
Sent: Sunday, 7 April 2019 6:39 PM
To: Rachel Curtis; Carol Maher; Dot Dumuid; Francois Fraysse; Timothy Olds; Adrian Esterman; Human Ethics
Subject: Human Ethics: Application approved

Dear Applicant

Re: Ethics protocol "Annual rhythms in weight gain, activity and diet compositions in parents – identifying opportunities to prevent cycles of weight gain" (Application ID: 201901)

Thank you for submitting your ethics protocol for consideration. Your protocol has been considered by the E1 Committee Review Group.

I am pleased to advise that your protocol has been granted ethics approval and meets the requirements of the National Statement on Ethical Conduct in Human Research. Please note that the E1 Committee Review Group's decision will be reported to the next meeting of the Human Research Ethics Committee for endorsement.

Please regard this email as formal notification of approval.

Ethics approval is always made on the basis of a number of conditions detailed at http://www.unisa.edu.au/res/forms/docs/humanresearchethics_conditions.doc; it is important that you are familiar with, and abide by, these conditions. It is also essential that you conduct all research according to UniSA guidelines, which can be found at http://www.unisa.edu.au/res/ethics/default.asp

Please note, if your project is a clinical trial you are required to register it in a publicly accessible trials registry prior to enrolment of the first participant (e.g. Australian New Zealand Clinical Trials Registry http://www.anzctr.org.au/) as a condition of ethics approval.

Best wishes for your research.

Executive Officer
UniSA's Human Research Ethics Committee CRICOS provider number 00121B

This is an automated email and cannot be replied to. Please direct your query to humanethics@unisa.edu.au.

Participant Information Sheet

Project Title: ARIA: Annual rhythms in adults' weight gain, activity and diet
Researcher: Associate Professor Carol Maher, B.Physio (Hons), PhD
Carol.Maher@unisa.edu.au
+61 8 8302 2315

You are invited to participate in a research study, titled ***ARIA: Annual rhythms in adults' weight gain, activity and diet*** which is being conducted by a team of health scientists led by Carol Maher at the University of South Australia. Participation in this study is voluntary and you are free to withdraw at any time without this affecting your status now or in the future. Before you decide to participate, it is important that you understand what you will be required to do and the risks and benefits of being involved.

What is the purpose of the study?
The aim of this study is to observe how lifestyle behaviours (activity, sleep, and dietary patterns), wellbeing, health and weight vary across different times of the year, and how lifestyle is associated with wellbeing, health and weight. The study will also examine whether changes in activity, dietary patterns and weight are similar between parents and their children. This study will help us understand how we might improve health and wellbeing not only for adults, but for families and children as well.

Why have I been asked to participate?
You have been asked to participate because you are a parent or guardian of a child who is enrolled in the Life on Holidays study at the University of South Australia. To participate, you must also be between 18 and 65 years old, live in the greater Adelaide region, have a home-based wireless internet connection and access to a compatible device such as a smartphone, tablet, laptop or desktop computer with Bluetooth, be able to read and speak English, and be ambulant (able to walk). You will be unable to participate if you are currently experiencing a life-threatening illness or condition that impacts your daily lifestyle and health.

What will I be required to do?
This study is designed to be as convenient for you as possible. If you agree to participate, we will schedule one face-to-face session at your home at a time that is suitable for you. We will measure your height, provide you with a Fitbit activity tracker and Fitbit electronic weight scales, and help you to set them up.

Following this session, you will be asked to wear your Fitbit activity tracker and weigh yourself daily throughout the year. Your activity, sleep and weight will be automatically recorded. You will also be asked to complete 8 online survey assessments about your health and diet. The survey will take about 45 minutes on the first occasion and 30 minutes for each subsequent occasion. These can be completed anywhere and on any device that has an internet connection (e.g. phone, tablet, laptop).

You must authorize us to access data from your Fitbit account during the study. You will authorize an application 'Fitnesslink' (developed for the University of South Australia by Portal Australia) to connect to your Fitbit account to collect and store your data for the duration of the study. The following data will be accessed from your Fitbit account:

- Sleep, sedentary time, light activity, moderate activity, and vigorous activity
- Weight
- Heart rate
- Device settings (name, battery level, last sync).

As part of the study, you must also consent to your data being matched with data from your child enrolled in the Life on Holidays Study and with data from your child's other parent or guardian, if also enrolled in this study.

How will you maintain my privacy?
Individuals' responses will be kept confidential and will not be identified in the reporting of the research. No information which could lead to identification of any individual will be released, unless required by law. We will take every care to store data securely and in a de-identified format (that is, your data will not be stored with your name, the name of your child, or the name of your child's other parent or guardian if enrolled). However, we cannot absolutely guarantee the confidentiality or anonymity of material transferred over the internet.

Data will be stored in electronic files in password-protected folders on the University server and password-protected hard drives on the researcher's computers. Paper copies will additionally be stored in a locked filing cabinet in Chief Investigator Carol Maher's office (CEA C7-41) at the University of South Australia. Data will be kept for a minimum of 5 years following the completion of the study.

What if I want to withdraw from the study?
You are free to withdraw from the study or to decline to answer specific questions on a questionnaire at any time. You are also free to withdraw your data up to one week (7 calendar days) after the scheduled date of your final assessment. After this time, we will begin to analyse your data. If you wish to withdraw your data, you must inform us via phone or email. If you withdraw from the study, you will be asked to return the study equipment (Fitbit activity monitor and weight scales).

What are the risks?
As we are observing your regular lifestyle, it is not anticipated that there are any risks to participation in this study beyond those encountered during everyday life.

What are the benefits?
There may not be any benefits to you from participating in this study, however, people often find their involvement in research to be interesting and personally rewarding. At the end of the study, you will be offered a personalised report on your lifestyle, health and wellbeing, including tips on how to maintain your health.

In appreciation of the time and effort involved in completing the activity, weight and survey assessments, you will be provided with $100 at the conclusion of the study. You will also be allowed to keep your Fitbit activity tracker and electronic weight scales at the conclusion of the study if you have remained enrolled for the full duration of the study.

Will I find out the results?
At the completion of this study, participants will be sent an email or posted a letter summarising the findings of the research.

If you have any questions or concerns regarding the study, please contact Carol Maher on 8302 2315 or Carol.Maher@unisa.edu.au.

This project has been approved by the University of South Australia's Human Research Ethics Committees. If you have any ethical concerns about the project or questions about your rights as a participant please contact the Executive Officer of these Committees, Tel: 8302 3118, Email: vicki.allen@unisa.edu.au.

Participants or third parties who wish to lodge a complaint about either the study or the way it is being conducted should contact the Executive Officer of UniSA HREC in the first instance, email: humanethics@unisa.edu.au or tel: 8302 3118.

University of South Australia

ARIA annual rhythms in adults' lifestyle and health

Participant Information Sheet

Project Title:	ARIA: Annual rhythms in adults' lifestyle and health
Researcher:	Associate Professor Carol Maher, B.Physio (Hons), PhD
Contact:	ariastudy@unisa.edu.au +61 8 8302 2065

You are invited to participate in a research study, titled ***ARIA: Annual rhythms in adults' lifestyle and health*** which is being conducted by a team of health scientists led by Carol Maher at the University of South Australia. Participation in this study is voluntary and you are free to withdraw at any time without this affecting your status now or in the future. Before you decide to participate, it is important that you understand what you will be required to do and the risks and benefits of being involved.

What is the purpose of the study?
The aim of this study is to observe how lifestyle behaviours (activity, sleep, and dietary patterns), wellbeing, health and weight vary across different times of the year, and how lifestyle is associated with wellbeing, health and weight. We are interested in studying the parents of children for this study.

Can I participate in this study?
To be eligible to participate in this study, you must be between 18 and 65 years old, be a parent or guardian of a primary school aged child (5-12 years), live in the greater Adelaide region, have a home-based wireless internet connection and access to a compatible device such as a smartphone, tablet, laptop or desktop computer with Bluetooth, be able to read and speak English, and be ambulant (able to walk).

You will be unable to participate if you are currently experiencing a life-threatening illness or condition that impacts your daily lifestyle and health, have a pacemaker or any other implanted medical device, or are pregnant or planning on becoming pregnant in the next 12 months.

What will I be required to do?
This study is designed to be as convenient for you as possible. If you agree to participate, we will schedule one face-to-face session at your home at a time that is suitable for you. We will measure your height, ask you to complete a brief survey, provide you with a Fitbit activity tracker and Fitbit electronic weight scales, and help you to set them up.

Following this session, you will be asked to wear your Fitbit activity tracker and weigh yourself daily throughout the year. Your activity, sleep and weight will be automatically recorded. You will also be asked to complete 8 online survey assessments about your health and diet. These surveys will take about 30 minutes on each occasion. These are best completed on a desktop, tablet or laptop with internet connection.

You must authorize us to access data from your Fitbit account during the study. You will authorize an application 'Fitnesslink' (developed for the University of South Australia by Portal Australia) to connect to your Fitbit account to collect and store your data for the duration of the study.

The following data will be accessed from your Fitbit account:

- Activity (sleep, sedentary time, light activity, moderate activity, vigorous activity, steps)
- Weight
- Heart rate
- Device settings (name, battery level, last sync).

You must notify us and cease using the weight scales if, at any time during the study, you have a pacemaker

or any other implanted medical device or become pregnant.

How will you maintain my privacy?
Individuals' responses will be kept confidential and will not be identified in the reporting of the research. No information which could lead to identification of any individual will be released, unless required by law. We will take every care to store data securely and in a de-identified format (that is, your data will not be stored with your name). However, we cannot absolutely guarantee the confidentiality or anonymity of material transferred over the internet.

Data will be stored in electronic files in password-protected folders on the University server and password-protected hard drives on the researcher's computers. Paper copies will additionally be stored in a locked filing cabinet in Chief Investigator Carol Maher's office (CEA C7-41) at the University of South Australia. Data will be kept for a minimum of 5 years following the completion of the study.

What if I want to withdraw from the study?
You are free to withdraw from the study or to decline to answer specific questions on a questionnaire at any time. You are also free to withdraw your data up to one week (7 calendar days) after the scheduled date of your final assessment. After this time, we will begin to analyse your data. If you wish to withdraw your data, you must inform us via phone or email. If you withdraw from the study, you will be asked to return the study equipment (Fitbit activity monitor and weight scales).

What are the risks?
As we are observing your regular lifestyle, it is not anticipated that there are any risks to participation in this study beyond those encountered during everyday life.

What are the benefits?
There may not be any benefits to you from participating in this study, however, people often find their involvement in research to be interesting and personally rewarding. At the end of the study, you will be offered a personalised report on your lifestyle, health and wellbeing, including tips on how to maintain your health.

In appreciation of the time and effort involved in completing the activity, weight and survey assessments, you will be provided with $100 at the conclusion of the study. You will also be allowed to keep your Fitbit activity tracker and electronic weight scales at the conclusion of the study if you have remained enrolled for the full duration of the study.

Will I find out the results?
At the completion of this study, participants will be sent an email or posted a letter summarising the findings of the research.

If you have any questions or concerns regarding the study, please contact us on +61 8 8302 2065 or ariastudy@unisa.edu.au

This project has been approved by the University of South Australia's Human Research Ethics Committees. If you have any ethical concerns about the project or questions about your rights as a participant please contact the Executive Officer of these Committees, Tel: 8302 3118, Email: vicki.allen@unisa.edu.au.

Participants or third parties who wish to lodge a complaint about either the study or the way it is being conducted should contact the Executive Officer of UniSA HREC in the first instance, email: humanethics@unisa.edu.au or tel: 8302 3118.

Appendix 3.4 - Participant Consent Form

This project has been approved by the University of South Australia's Human Research Ethics Committee. If you have any ethical concerns about the project or questions about your rights as a participant please contact the Executive Officer of this Committee, Tel: +61 8 8302 3118; Email: humanethics@unisa.edu.au

SECTION 1: CONTACT AND PROJECT DETAILS

Researcher's Full Name:	Associate Professor Carol Maher
Contact Details:	Carol.Maher@unisa.edu.au Tel: +61 8 8302 2315
Protocol Number:	201901
Project Title:	Annual rhythms in weight gain, activity and diet in parents

SECTION 2: CERTIFICATION

Participant Certification

In signing this form, I confirm that:

- I have read the Participant Information Sheet and the nature and purpose of the research project has been explained to me. I understand and agree to take part.
- I understand the purpose of the research project and my involvement in it.
- I understand that I may refuse to answer specific questions in the questionnaire and withdraw from the research project at any stage and that this will not affect my status now or in the future.
- I consent to having my data matched with data from my child enrolled in the Life on Holidays study and data from my child's other parent or guardian, if also enrolled in this study.
- I understand that I may withdraw my data within 1 week after the scheduled date of my final assessment.
- I understand that while information gained during the study may be published, I will not be identified and my personal results will remain confidential, unless required by law.
- I understand that while the researcher will take every care to maintain my confidentiality, confidentiality or anonymity of material transferred over the internet cannot be absolutely guaranteed.
- I understand the statement in the information sheet concerning payment to me for taking part in the study.

Participant Signature	*Printed Name*	*Date*

Researcher Certification

I have explained the study to subject and consider that he/she understands what is involved.

Researcher Signature	*Printed Name*	*Date*

University of South Australia

ARIA: Annual rhythms in adults' lifestyle and health

Home visit standard operating procedure

ARIA
annual rhythms in adults' lifestyle and health

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Introduction

Scope

This document describes the steps involved in conducting home visits with participants for the ARIA study. The purpose of the home visit is to provide study devices and gain baseline measures. Should the session be conducted at a different location, such as a UniSA campus, please refer to the *Alternate location standard operating procedure* document.

Contacts

Principal investigator - Dr Carol Maher
UniSA City East campus
Email: Carol.Maher@unisa.edu.au
Phone: +61 8 8302 2315

Project manager – Dr Rachel Curtis
UniSA City East campus
Email: Rachel.Curtis@unisa.edu.au
Phone +61 8 8302 2455

Section 1 - Prior to home visit tasks

Step 1 – Collect resources

- The following items will need to be taken on each home visit:
    - Home visit schedule
    - Stadiometer
    - Fitbit Charge 3 monitor(s) – one per participant
    - Charge 3 replacement bands
    - Fitbit Aria 2 – one per household
    - Document folder – check that it contains the following:
        - Home visit checklist
        - Participant contact details sheet and baseline survey
        - Participant Information sheet
        - Blank consent form
        - FAQ sheet
        - Weigh-in wall reminder
    - Standard Operating Procedure manual
    - Pens

Step 2 – Participant details

- Use the home visit schedule to record the Participant ID on the home visit checklist, participant contact details sheet, and all pages of the baseline survey.
- Record if consent form has been completed. If it has not been completed, this will need to be done at the beginning of the home visit.
- Do not additional participant information to any paperwork beyond what is requested, this is to maintain confidentiality.

Step 3 - Update Fitbit Charge 3

- Each Fitbit Charge 3 will need to be charged along with a software update performed. This can take up to 30 minutes to complete. The software update will start once the Charge 3 is linked to a Fitbit account via the mobile app.
- Charge the monitor via the supplied cable. Open the Fitbit app using an existing user account. Open the account tab (Image 1), click the 'set up a device' link and follow the prompts to complete the software update (Image 2).

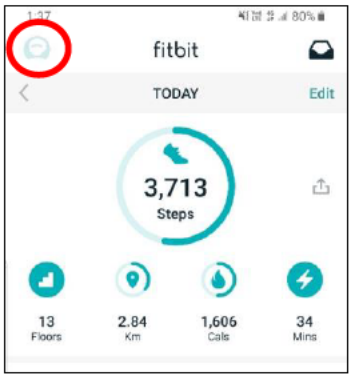


Image 1

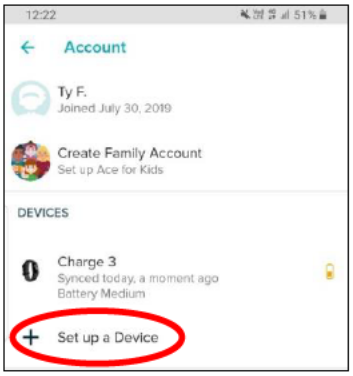


Image 2

Step 4 – Location sharing via Google Maps

- Staff will attend home visits alone and generally after normal working hours. An additional team member will be rostered on as a 'contact person' during scheduled home visits for additional support and safety. This staff member will monitor the ARIA study email (ariastudy@unisa.edu.au) and be available via mobile phone (number provided on the home visit schedule). To assist with this role, and as a safety measure, you are to share your real-time GPS location via Google Maps during work hours. This information will only be accessible to the rostered-on contact person as it will be sent via SMS.
- The following instructions are for the Android version of Google Maps, it may differ slightly for iOS or Windows.
- To share your real-time location, open the Google Maps app, click on the menu (top left corner, 3 horizontal bars) and select 'Location sharing'. Next, select 'Until you turn it off' for real-time location, below this should be a row of recent contacts, scroll to the right until you find the 'more' button at the end, click on this.
- On the following screen enter the mobile number of the contact person in the top bar, then click 'send'. You will be taken to your SMS message app and a pre-filled message will be ready to send, click send to share your location.
- The contact person will be able to open the link you shared and see your real-time location until you turn off sharing. This will be covered in the 'After home visit' section.

Section 2 - During home visit

Step 1 – Safe arrival SMS

- Once you have arrived at the home visit, and whilst in front of the participant, send a brief arrival SMS to the rostered contact person (name and number supplied on home visit schedule). This is an important safety measure to let another member on the team know you arrived safely.

Step 2 – Project introduction, participant expectations and consent form

- Begin the visit by refreshing project details as per the 'participant information sheet'.
- Explain to the participant the purpose of the study and why it's important:
    - Evidence suggests there are cyclical spikes in weight gain due to lifestyle and health behaviours, which accrue over time.
    - A better understanding of when these spikes occur will enable the design and implementation of interventions at the time they are needed most, altering obesity and disease trajectories.
    - This study is a first of its kind in Australia and there is a one-off time-limited window of opportunity to perform this study.
- Explain to the participant what is expected of them during the study, this will include:
    - Wearing an activity monitor continuously (including during sleep, not during water activities) and weighing themselves on a scale daily.
    - Complete eight online follow-up surveys of about 30 minutes duration. These will be spread throughout the 13-month study period. Participants will be provided details via email prior to each survey.
    - The purpose of the study is ***not*** for participants to try to lose weight or change their activity levels, the study hopes to monitor usual activity patterns.
- Advise the participant that device activity will be monitored remotely to check for continued participation in the study. Where no recent activity has been observed, a follow-up SMS reminder can be expected in the first instance. Should this continue a follow-up phone call can then be expected to check-in with the participant. Information that will be monitored to help determine non-compliance will include *battery status, syncing frequency, monitor wear time and weigh-in frequency*. Participants who are using and syncing devices regularly will not be contacted to check on compliance.
- Collect completed participant consent forms if not previously supplied. Provide a consent form to the participant if needed, blank copies are found in the document folder. Consent must be signed by the participant and research assistant prior to commencing any further steps.

Step 3 – Measure height

- A Leister Height Measure MKII stadiometer is to be used. Assemble the stadiometer and position the baseplate on a firm, level surface with the rear stabilisers resting against a wall.
- The participant will need to remove shoes, socks, along with any hat or hair accessories.
- Have the participant stand on the footprint markers with heels together and touching the backstop. Ensure the participants legs are straight, buttocks and upper back touching the upright, shoulders relaxed and arms by sides (image 3). Position the participant's head in the Frankfurt Plane (image 4). This is achieved by aligning the lower edge of the eye socket with the upper margin of the ear canal along a horizontal line.
- Lower the measuring arm firmly onto the head and record height on the participant's baseline survey to the nearest 0.1cm.
- Repeat the measure and use the mean of the two results as the participant's height. If the difference between the two measures is greater than 0.5cm, conduct a third measure and use the median of the three results as the participant's height.



Image 3

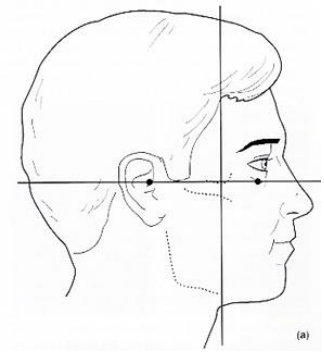


Image 4

Step 4 – Baseline survey

- Ask the participant to confirm their contact details by completing the participant contact details sheet.
- Ask the participant to complete the baseline survey, ensuring height has already been recorded.
- Once the survey has been completed, initial the bottom right corner of each page of the participant's survey.

Step 5 – Fitbit app and Fitbit Charge 3 set up

- Install the Fitbit app on the participant's mobile phone via the relevant app store (iOS: App Store, Android: Google Play, Windows: Windows Store). Find the app by search 'Fitbit'. The official app is developed by 'Fitbit, Inc.'. Image 5 depicts how the app appears on Google Play.

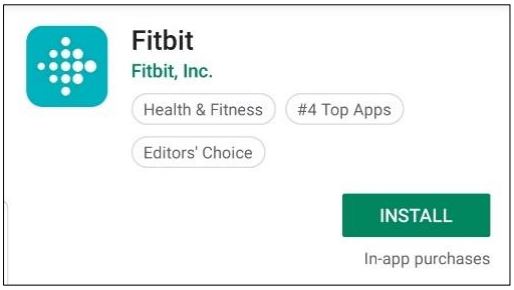


Image 5

- Once installed, set up a new user account as per images 6 to 10.

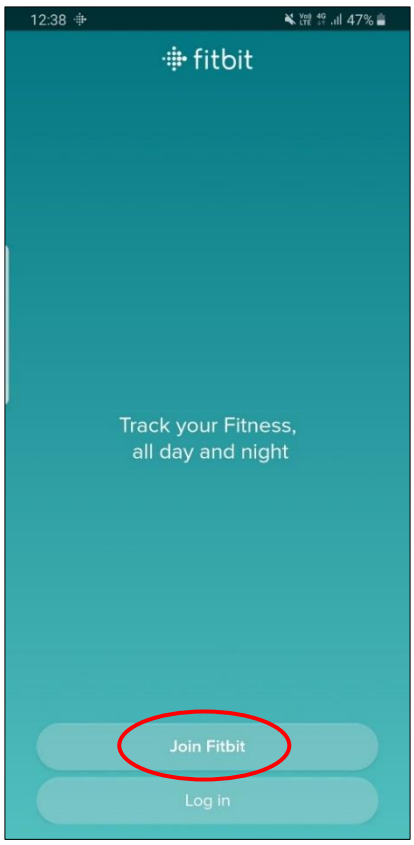


Image 6

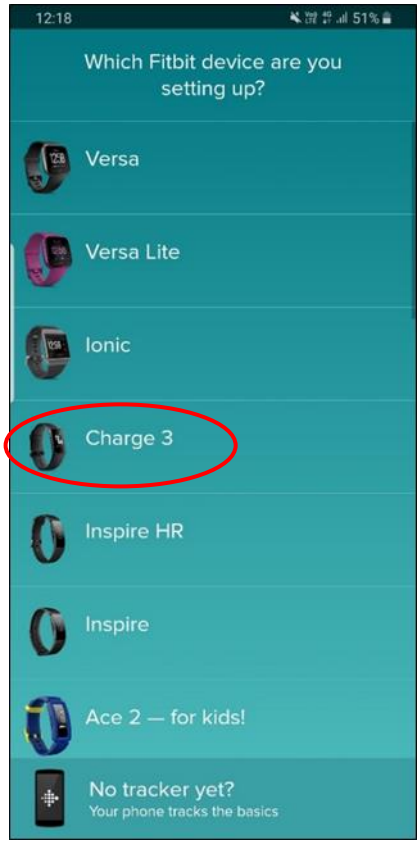


Image 7

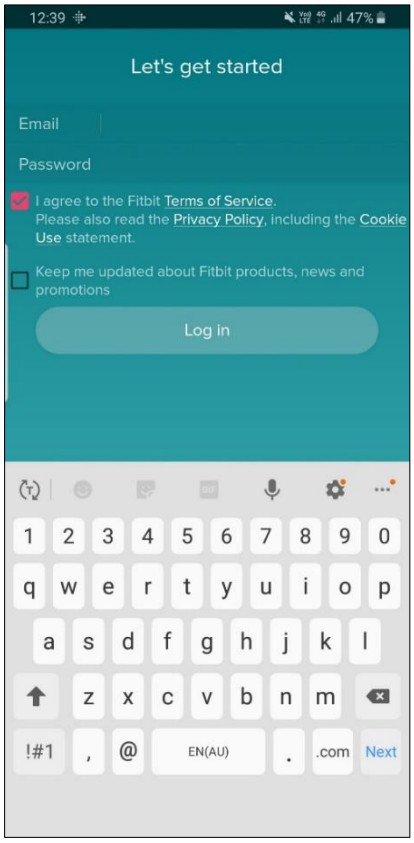


Image 8

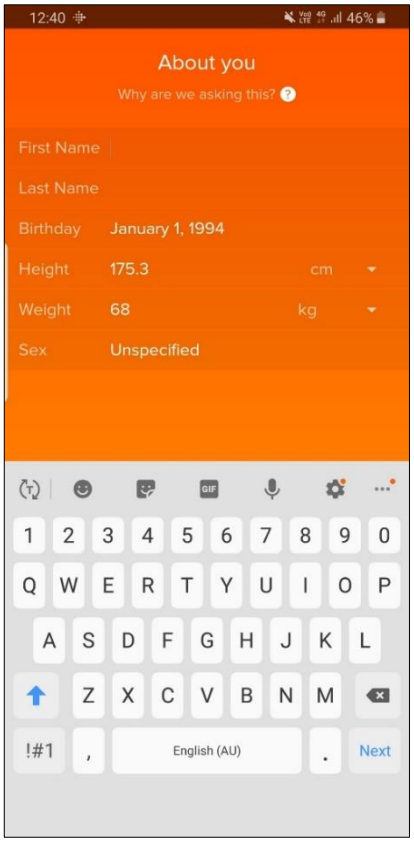


Image 9

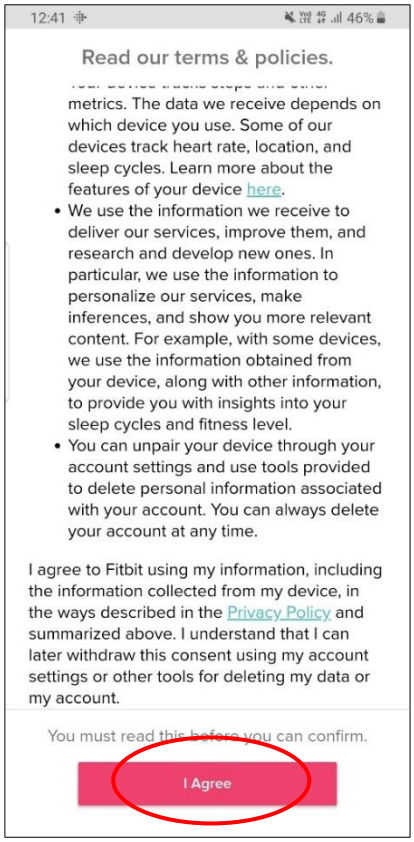


Image 10

- If the participant already has a Fitbit user account and would like to use it during the study, they will need to log in to this account and remove any existing linked devices. To do this open the account tab (image 1), click on the device to remove and then click on the rubbish bin icon in the top right corner.
- Record the participant's chosen username on the *Home visit checklist*. Explain to the participant it is preferred they keep the same username during the study. If they decide to change their username at any point during their participation in the study, they will need to update the project team with this information via the project email, ariastudy@unisa.edu.au.
- Height – For both new and existing user accounts, enter the participant's height as measured earlier in the home visit. For new accounts this is done during the initial account set up, for exiting users this will need to be manually updated via the participant's user profile. To do this, open the account tab (image 1), click on the username, click on 'personal', finally click on 'height' and enter height and click 'save' in the top right corner.
- Weight - For new user accounts, enter an estimate of weight. No weight is needed for existing user accounts. Weight will be updated once the Aria 2 scales are set up and linked.
- Within the account set up there is the option to also set up a Fitbit device. At this point commence set up of the Charge 3. Follow the prompts to link the Charge 3 with the participant's Fitbit account as per images 11 to 15.

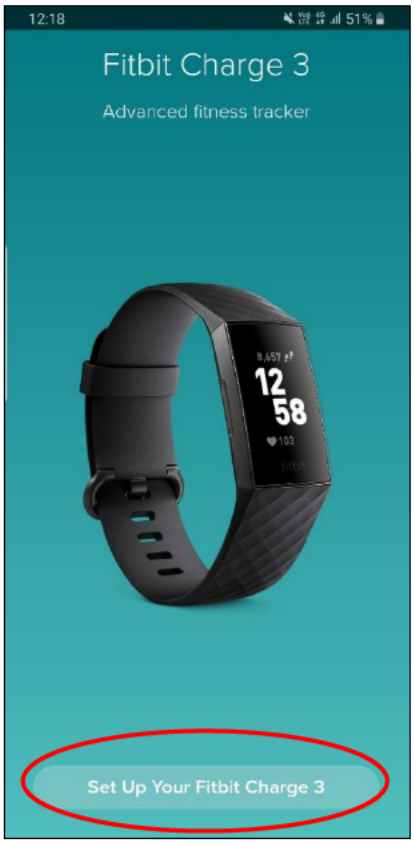


Image 11

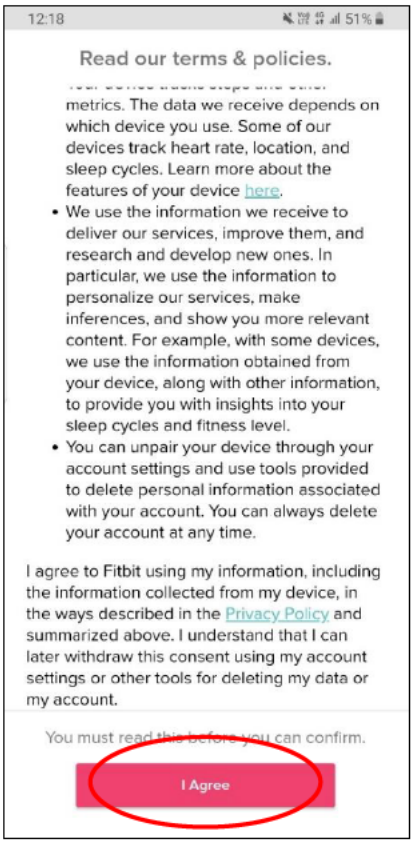


Image 12



Image 13

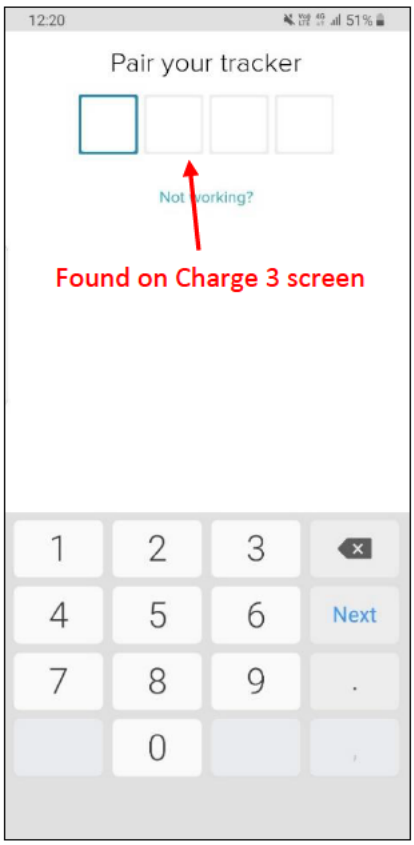


Image 14

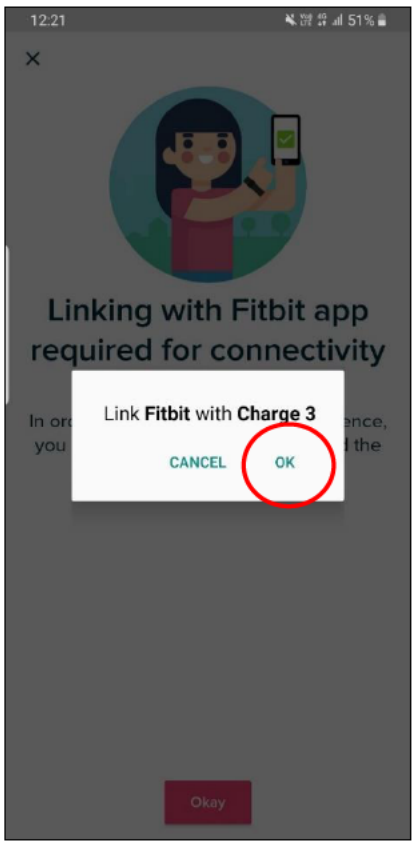


Image 15

- *STUDY REQUIREMENT REMINDER* - Advise the participant of the following:
    - Activity monitor to be worn continuously each day, this includes during sleep (to capture sleep data).
    - Remove activity monitor during showers and water activities to minimise potential for damage. Devices are waterproof, removal is a precaution.
    - Sync Charge 3 regularly (every 5 days), keep auto-sync setting on for simplicity.

Step 6 – Fitbit Aria 2 set up

- Prior to set up ensure the participant has the name and password of their home Wi-Fi network available.
- If the participant does not have a home Wi-Fi network, it is possible to use their mobile phone as a mobile hotspot if they are happy to do so. Set up instructions for creating a mobile hotspot is phone specific. Generally, it is done via the settings menu under 'connections' -> 'mobile hotspot and tethering' for Android or 'mobile data' -> 'personal hotspot' for iOS.
- If the participant does not have home Wi-Fi and does not wish to use a mobile hotspot, they will need to record their weight manually, refer to step 7 for further detail.
- Aria 2 is set up via the Fitbit app. If there are two participants who will be using the scales a primary user account will need to be decided as both users will be set up via this primary account. Ensure both user accounts have been created prior to commencing the set-up of Aria 2.
- To begin set up, open the account tab on the home screen (image 1). Select 'set up a device' under the Devices heading (image 2).
- Follow the prompts to set up and link Aria 2 using the primary user's account as per images 16 to 24. Record the participant's icon on their FAQ sheet

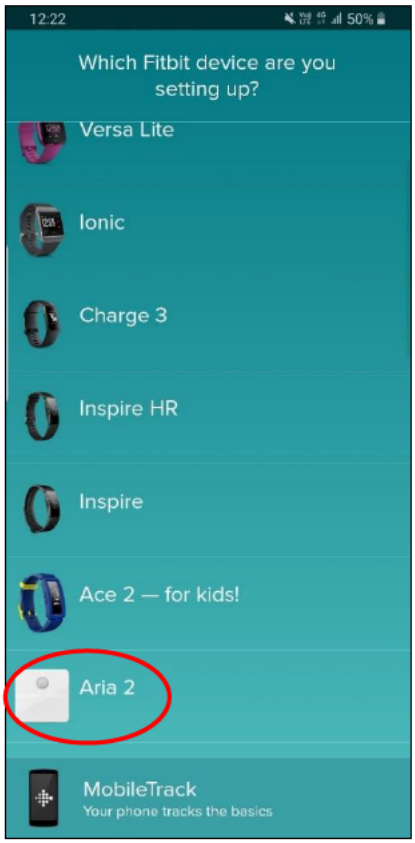


Image 16



Image 17

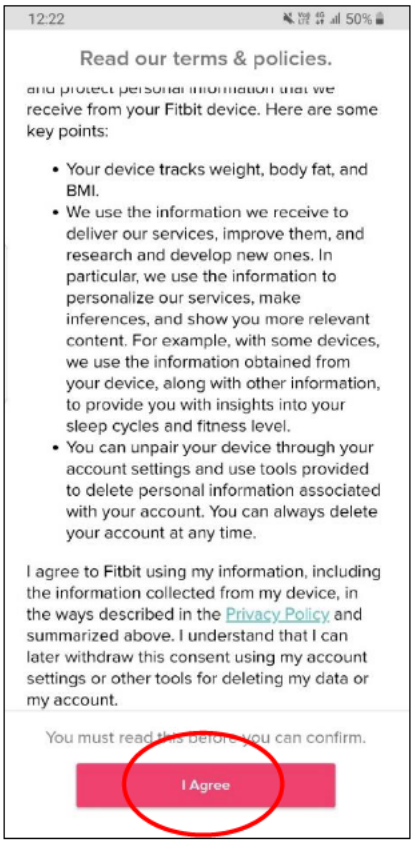


Image 18

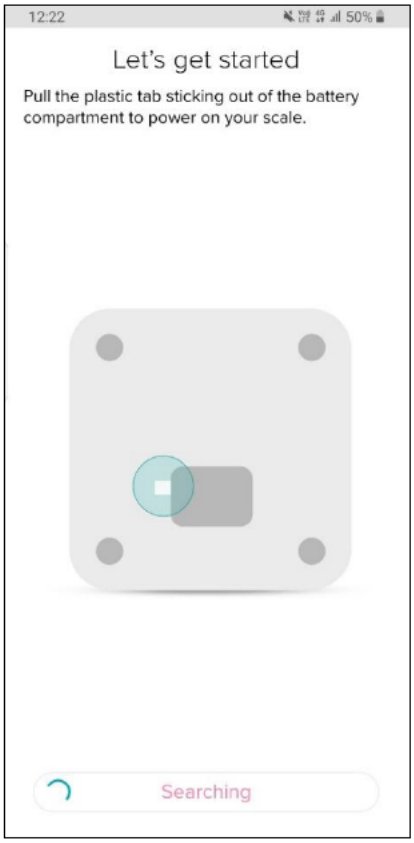


Image 19

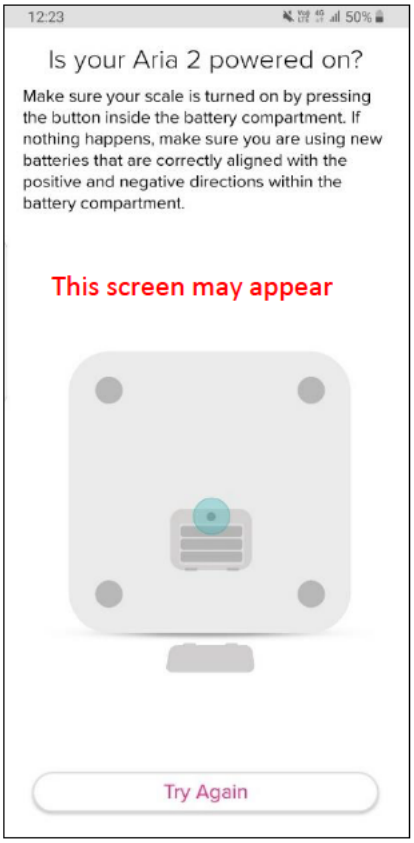


Image 20

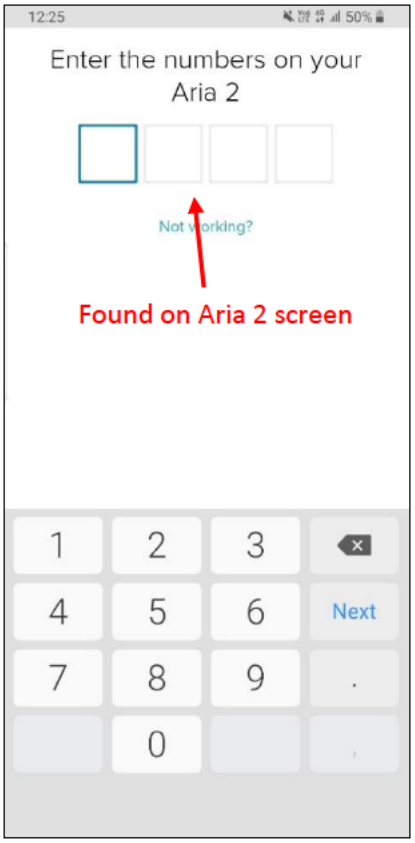


Image 21

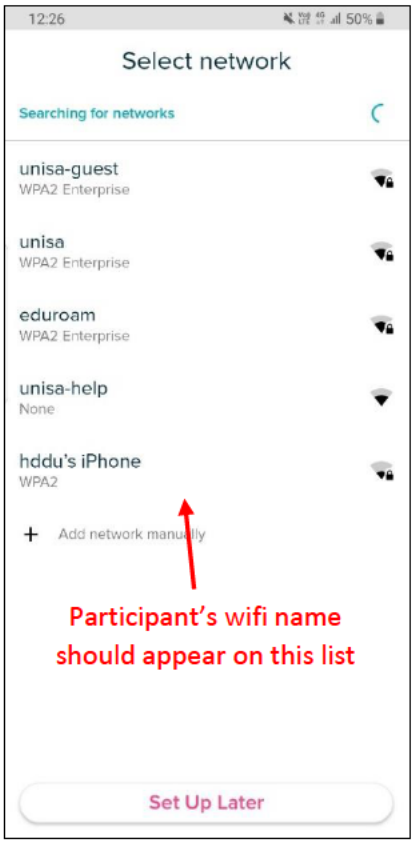


Image 22

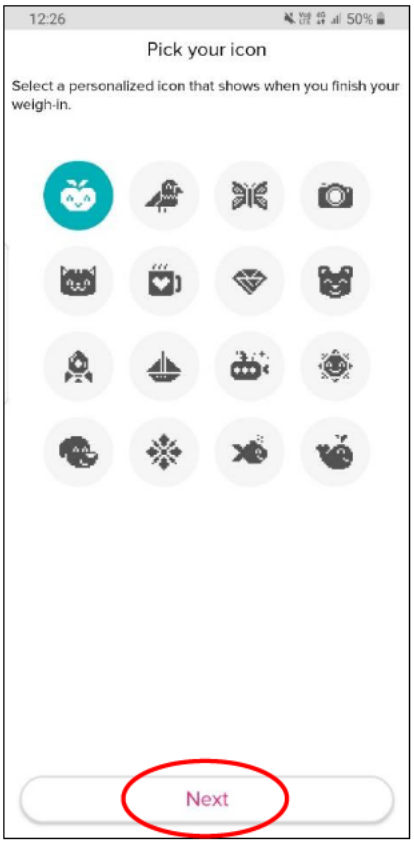


Image 23

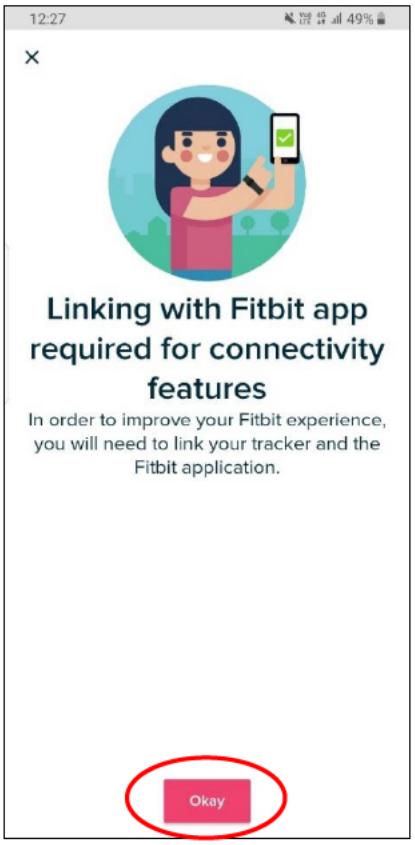


Image 24

- Set up a secondary user as required, as per images 25 and 26. Once the email invitation has been sent, have the second participant access the email via their inbox and click on the 'accept invite' link within. The secondary user will then be taken to the Fitbit app where they will need to select their preferred icon as per image 23 and link Aria 2 with their Fitbit app as per image 24. Record the participant's icon on their FAQ sheet.



Image 25

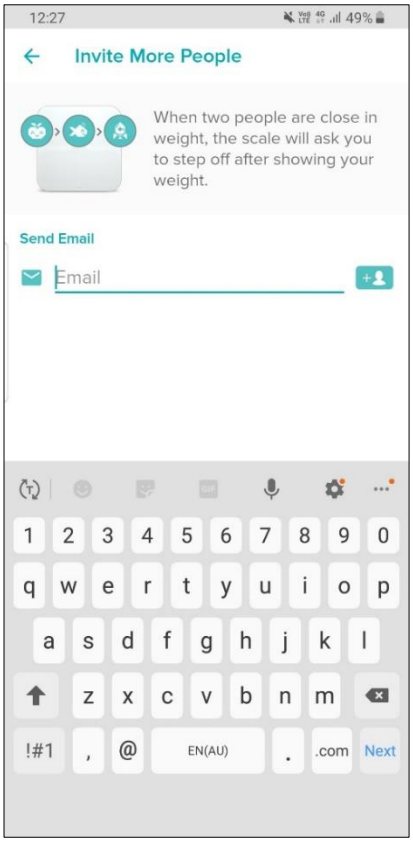


Image 26

- Check the account tab to ensure both devices are linked to the participant's account (image 1 and 2).

Step 7 – Measuring weight with the Aria 2 scale

- For accurate results, the scale must be placed on a hard, flat surface and the participant must be barefoot.
- Ask the participant to step on the scale to initiate a measurement. After a short period of time, the display will advise the participant to step off, as indicated by two footprints moving down the screen. Once the participant steps off, their weight will be displayed briefly. If the participant will be manually entering their weight (no Wi-Fi) it is important they are ready to write this number down. If Wi-Fi is set up on the scale it will automatically sync with the participant's Fitbit account.
- When there are two participants sharing an Aria 2 scale, the scale will need to identify which participant is on the scale. If there is a reasonable difference in weight between both users, the scale will automatically detect the correct user. If the weight measures are similar the scale will request confirmation. This is done by displaying the icon of the most likely user (closest weight and body fat) along with a tick on the left of the icon, and a cross on the right. If the icon is of the correct participant, select the tick by pushing on the left side of the scale surface and if it is incorrect, select the cross by pushing on the right side.
- *STUDY REQUIREMENT REMINDER* - Advise the participant of the following:

- The should use scale once a day to perform weigh-ins.
- Be consistent with time of day weigh-ins are performed. The preferred option is morning however they may wish to do their weigh-in before showering, which may be in the evening.
- An ideal weigh-in is performed wearing minimal clothing, before food and after using the restroom.
- Aria 2 will sync automatically unless there is an error (you cannot manually sync the scales).

Step 8 – Notifications and privacy settings

- App notifications should be modified to only allow notifications for 'low battery'. To modify notifications, open the accounts tab, scroll down and click on 'notifications'. Turn off each notification other than low battery (image 27).
- Privacy settings will also need to be modified to the highest level available. To modify, open the accounts tab, scroll down and click on 'privacy'. Change all settings to private. The only item that is not able to be set to private is 'average daily step count', change this to the 'friends' option (image 28).

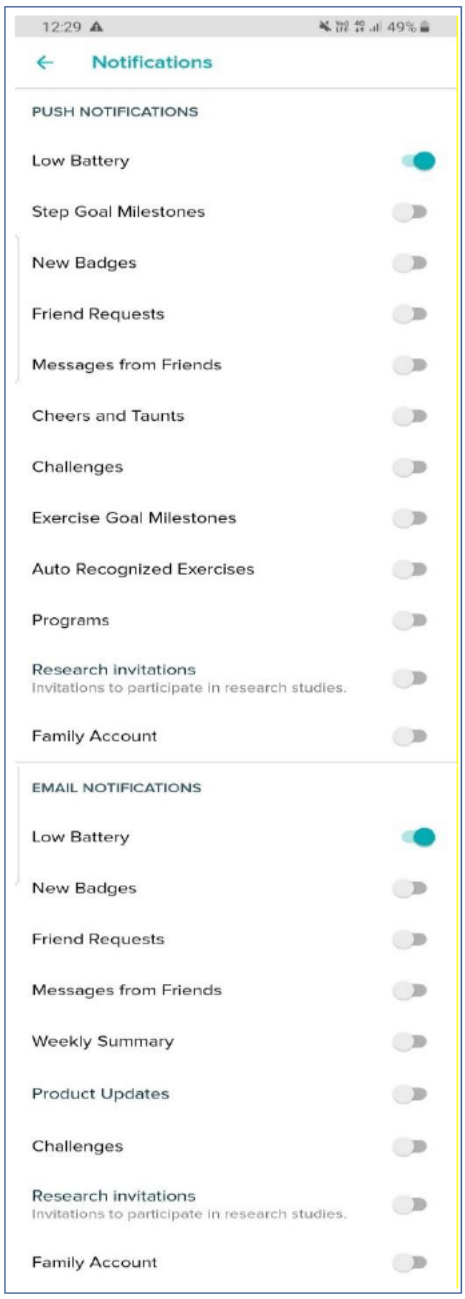


Image 27

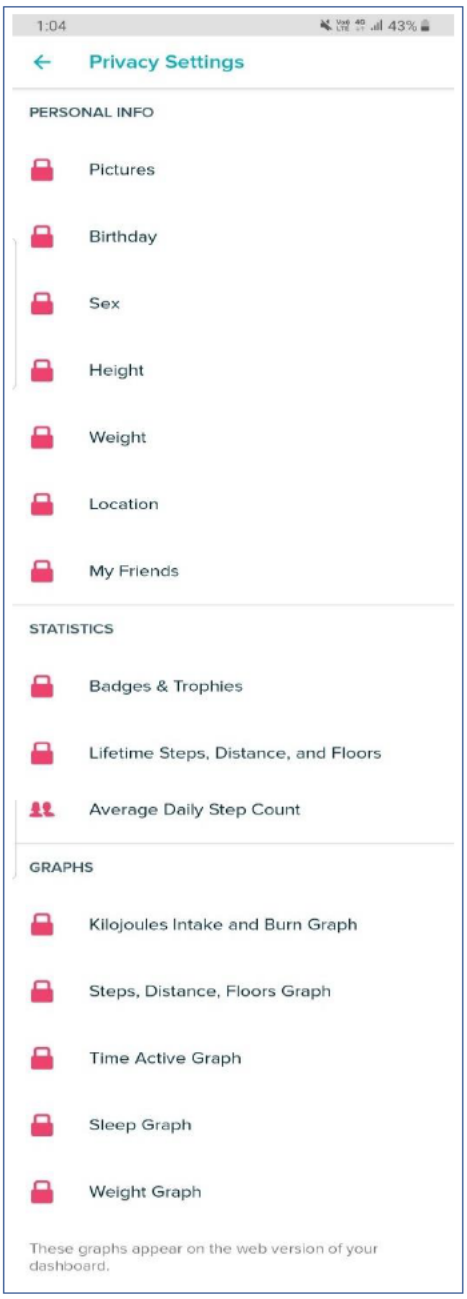


Image 28

Step 9 – Authorise FitnessLink software

- To allow remote data collection from a participant's Fitbit account, software called FitnessLink will need to be authorised as a Third-Party App.
- To authorise FitnessLink, have the participant go to the FitnessLink weblink, www.Fitnesslink.net.au, via their web browser. The participant will need to enter their Fitbit account login detail and follow the prompts once logged in. All data collection parameters listed should be selected.
- To check FitnessLink has been authorised successfully, open the accounts tab in the Fitbit app, click on 'Manage Data', click on 'Manage Third Party Apps' and then login using the participants Fitbit account. Image 29 shows how successful authorisation should appear.

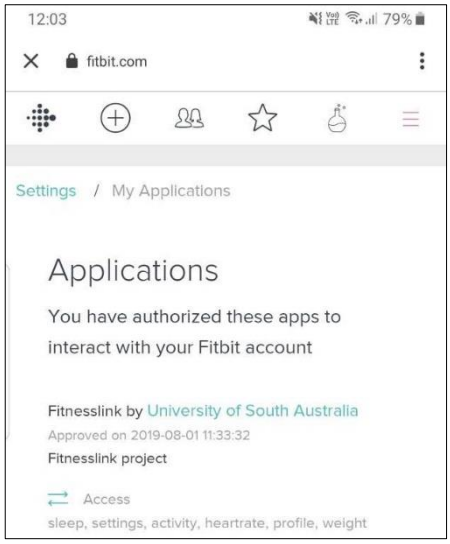


Image 29

Step 10 - Provide participant resources

- Leave a copy of the **FAQ sheet** and **laminated weigh-in reminder** with participants (one per household). The FAQ sheet details common questions about the devices and addresses basic troubleshooting needs.
- Provide the participant with their choice of extra Fitbit band.
- Advise the participant to contact the project team via the project email, ariastudy@unisa.edu.au if they require further support or have any questions regarding the project.
- Remind the participant to wear the Charge 3 continuously and perform a daily weigh-in throughout their 12-month participation in the study. Additionally, the participant needs to keep their devices charged and syncing frequently to their Fitbit account to prevent loss of data.
- Advise the participant that they will be emailed their first online survey in December.

Step 11 - Packaging

- Collect all boxes and packaging from Fitbit devices. Only leave devices and charge cable with participants.

Step 12 - Home visit checklist

- Prior to leaving the home visit make sure all points on the home visit checklist have been completed and all equipment/resources not to be left with participants are collected.

Step 13 - Safe completion SMS

- After leaving the home address, and once back in your vehicle, send a brief SMS to the contact person (number on home visit schedule) advising the session has been completed.

You may wish to drive a short distance away from the address and stop before sending the SMS.

- The contact person will estimate a completion time based on the time of your arrival SMS. Single participant visits are estimated to take 45 minutes and double participant visits, 60 minutes. If they have not received an SMS within 15 minutes of this estimated completion time you will receive a phone call to check in and ensure you are safe. The contact person will also check your real-time location as needed. If you anticipate the session running longer than expected please send an SMS to update your estimated completion time. This update is in addition to the safe completion SMS.

Section 3 - After the home visit

Step 1 – Turn off location sharing

- Turn off location sharing via Google Maps. To do this, open the app, select the menu followed by 'Location sharing', on this screen click on the cross in the bottom right corner next to 'sharing via link'.

Step 2 – Survey data entry

- Baseline paper-based surveys are to be entered on an electronic spreadsheet as soon as possible after the home visit. The spreadsheet will be a Google document, allowing for remote data entry as required. Access to the spreadsheet will be provided prior to the home visits.

Step 3 – Return resources

- Return all equipment and resources to Rachel Curtis in C7-34.
- Return all completed paperwork to Rachel Curtis in C7-34, including:
    - Consent forms
    - Participant contact details sheets
    - Baseline surveys
    - Home visit checklist
    - Home visit schedule

Appendix

a)	**Home visit checklist**
b)	**Frequently Asked Questions document**
c)	**Home visit schedule**
d)	**Weigh-in wall reminder**

ARIA study - Home visit checklist

Pre-visit office tasks

Consent form returned prior to home visit?

◯ Yes ◯ No

Resources collected (C7-34)

- ◯ Home visit schedule
- ◯ Stadiometer
- ◯ Fitbit Charge 3 – one per participant
- ◯ Charge 3 replacement bands
- ◯ Fitbit Aria 2 – one per household
- ◯ Document folder – check that it contains the following:
  - Participant contact details sheet and survey (add ID to all pages)
  - Information sheet
  - Consent form
  - FAQ sheet
  - Laminated weigh-in reminder sheet
- ◯ Standard Operating Procedure manual
- ◯ Pens

Home visit

Prior to visit

- ◯ Real-time location shared via Google Maps
- ◯ 'Check-in' SMS sent to contact person (number on home visit schedule)

During visit

- ◯ Project information provided
- ◯ Consent form completed and signed by RA **OR** ◯ N/A (completed prior to home visit)
- ◯ Height measured and recorded on survey
- ◯ Participant contact details sheet completed
- ◯ Survey completed AND each page initialled by RA
- ◯ Fitbit app installed and account created **OR** ◯ Successful log-in to existing account
- ◯ Fitbit username recorded at top of this checklist
- ◯ Charge 3 set-up
- ◯ Aria 2 set-up
- ◯ FitnessLink authorised (www.Fitnesslink.net.au)
- ◯ Updated privacy and notification settings
- ◯ FAQ sheet and weigh-in reminder provided
- ◯ Packaging collected

After visit

- ◯ 'Check-out' SMS sent to contact person after leaving home/site
- ◯ Once all visits completed, turn off real-time location sharing

Post-visit office tasks

- ◯ Resources returned and paperwork stored in C7-34
- ◯ Survey data entry
- ◯ Paperwork replenished in resource folder as needed

Completed by: ……

Date: ……

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Participant ID:

Fitbit username:

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Frequently Asked Questions

Information adapted from help articles on www.fitbit.com

1. Which icon did I chose on the Aria 2 scale?



Primary user is: .....

Secondary user is: .....

(as needed)

2. What do I do if I've selected the wrong icon on the Aria 2 scale after weighing in?

Tap the Today tab, and tap your profile picture. Tap **Aria 2** and tap **Recent weigh-ins**. Open the weigh-in that was assigned to the wrong icon/user and reassign it to the correct user.

3. How do I sync my Aria 2 scale with the Fitbit app?

After weighing in, the scale should display a progress bar, followed by a check mark, which indicates the new measurement synced successfully. If the scale doesn't sync, you may see an error message (NO SYNC, CONNECTION ERROR, NO WIFI, etc.). Try weighing yourself again, if the problem persists, try the following tips:

- Check that your Wi-Fi router is on and working.
- Remove the batteries from your scale for 10 seconds, then reinsert them to restart your scale.
- Your scale may be too far away from your router. Try moving the scale closer to your Wi-Fi router.
- If you've made any changes to your network (new router, name and/or password) see **Question 4**.

4. How do I reconnect my Aria 2 scale to my wireless network?

With your Aria 2 scale and Wi-Fi router nearby, open the Fitbit app on your mobile phone (Bluetooth on). On the Today tab, tap your profile picture, then tap Aria 2. Tap Wi-Fi Network or Pair Scale to Different Network (depending on the device). Tap Next and follow the on-screen instructions to reconnect your scale to your network.

5. Why isn't my Aria 2 scale turning on?

If your scale doesn't turn on when you stand on it, you may need to replace the batteries (3x AA batteries). The battery panel is located on the underside of the scale. Batteries should last 6-12 months.

6. How do I add an additional user on the Aria 2 scale?

Tap the Today tab, and tap your profile picture. Tap **Aria 2** and tap **Users**. Tap on the + sign in the bottom right corner and follow the prompts to add the additional user.

7. How do I sync my Charge 3 activity monitor with the Fitbit app?

To sync your Charge 3 with the Fitbit app, open the app and slide down on the home screen. This should commence syncing. Additionally, ensure that All-day sync is turned on to make syncing automatic, be aware this

will reduce battery life on your Charge 3 and phone. If your Charge 3 is still not syncing, there are several troubleshooting steps to try.

- Check that your mobile phone's Bluetooth is turned on, and has cellular data or Wi-Fi connected.
- Update your Fitbit app as required via your app store.
- Ensure your Charge 3's battery isn't critically low.

If your Fitbit device still won't sync, try these steps:

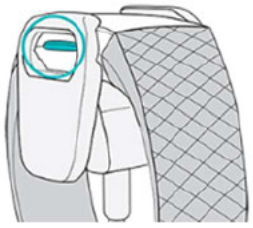
- Close and reopen the Fitbit app.
- Go to Settings > Bluetooth and turn Bluetooth off and back on.
- Open the Fitbit app.
- If your Fitbit device didn't sync, restart it.
- Finally, uninstall and reinstall the Fitbit app if your Charge 3 still doesn't sync.

8. How do I charge my Charge 3 activity monitor?

Plug the charging cable into a USB port on your computer, a UL-certified USB wall charger, or another low-energy device. Attach the other end of the cable to your Fitbit device. Charging your device to 100% may take 1-2 hours.

9. How do I attach the charging cable to my Charge 3 activity monitor?

Clip the end of the charging cable to the port on the back of the Charge 3. The pins on the charging cable must lock securely with the port. Make sure the button on your Charge 3 is aligned with the button opening on the charging cable. The connection is secure when the Charge 3 vibrates, and a battery icon appears on the screen.



10. How do I check the battery level on my Charge 3 activity monitor?

Swipe down on the Today tab of the Fitbit app to see your battery level in the top left corner or see your battery level on the Charge 3 screen. You can also see the battery life on the screen of the Charge 3. Double-tap the screen to bring up the watch face, then swipe up once. The battery life is displayed at the top of the screen.

11. How do I reconnect my Charge 3 activity monitor or Aria 2 scale to my Fitbit account?

Tap the Today tab, and tap your profile picture. Tap **Set Up a Device**. Choose your device and follow the on-screen instructions to continue.

12. How do I reinstall the Fitbit app?

The Fitbit mobile app can be reinstalled via your phone's app store (iOS: App Store, Android: Google Play, Windows: Windows Store). Find the app by searching 'Fitbit' in the app store. The image below depicts how the app appears on Google Play. Once downloaded ensure you login using your ARIA study participant account.



13. How do I update the time zone of my Charge 3?

Open the Fitbit app and perform a manual sync by pulling down on the home screen.

14. How do I restart my Fitbit Charge 3?

Attach your Charge 3 to its charging cable, and ensure it is charging. Hold down the touch-sensitive button on the side for 5-8 seconds until a smiling face appears on the screen. After a few moments the screen will return to the watch face. This means you have successfully restarted the device. This *does not delete* any user data and can be useful if your device isn't synching or recording properly.

15. Where can I get more help with the Fitbit devices and mobile app?

For more detailed troubleshooting and product manuals go to Fitbit's website, www.fitbit.com, and open the help menu or open the relevant product page. If you are still unable to resolve your issue, please contact the ARIA project team via email, ariastudy@unisa.edu.au.

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ARIA study - Home visit schedule

Visit 1	Participant 1		Participant 2	
Name(s)				
Participant ID(s)				
Phone number(s)				
Consent form completed?	YES	NO	YES	NO
Visit time/date				
Address				
SMS to contact person (number at bottom of page)	Arrival time:		Completion time:	

Visit 2	Participant 1		Participant 2	
Name(s)				
Participant ID(s)				
Phone number(s)				
Consent form completed?	YES	NO	YES	NO
Visit time/date				
Address				
SMS to contact person (number at bottom of page)	Arrival time:		Completion time:	

Visit 3	Participant 1		Participant 2	
Name(s)				
Participant ID(s)				
Phone number(s)				
Consent form completed?	YES	NO	YES	NO
Visit time/date				
Address				
SMS to contact person (number at bottom of page)	Arrival time:		Completion time:	

Contact person: ……..

Phone number: ……..

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Have you weighed yourself today?

Keep it consistent, aim to weigh at the same time each day, with minimal clothes, before meals and after using the restroom.

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ARIA annual rhythms in adults' lifestyle and health

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ARIA: annual rhythms in adults' lifestyle and health

Thank you for your interest in the ARIA study! Please follow the prompts below to provide your consent to participate in the study and to complete the online survey. If you have not yet read the Participant Information Sheet, you can view it **here**. If you have any questions, please get in touch with us at ariastudy@unisa.edu.au

Please read each statement carefully, type your name in the box below, and click "Continue" to consent and begin the online survey.

- I have read the Participant Information Sheet and the nature and purpose of the research project has been explained to me. I understand and agree to take part.
- I understand the purpose of the research project and my involvement in it.
- I understand that I may refuse to answer specific questions in the questionnaire and withdraw from the research project at any stage and that this will not affect my status now or in the future.
- I understand that my data will be stored in electronic files in password-protected folders on the University server and password-protected hard drives on the researcher's computers. Paper copies will additionally be stored in a locked filing cabinet in Chief Investigator Carol Maher's office (CEA C7-41) at the University of South Australia. I understand that my data will be kept for a minimum of 5 years following the completion of the study.
- I consent to having my data matched with data collected from my child enrolled in the Life on Holidays study and data from my child's other parent or guardian, if also enrolled in this study.
- I understand that I may withdraw my data within 1 week after the scheduled date of my final assessment.
- I understand that while information gained during the study may be published, I will not be identified and my personal results will remain confidential, unless required by law.
- I understand that while the researcher will take every care to maintain my confidentiality, confidentiality or anonymity of material transferred over the internet cannot be absolutely guaranteed.
- I understand the statement in the information sheet concerning payment to me for taking part in the study.

Name

Continue

This project has been approved by the University of South Australia's Human Research Ethics Committees. If you have any ethical concerns about the project or questions about your rights as a participant please contact the Executive Officer of these Committees, Tel: 8302 3118, Email: vicki.allen@unisa.edu.au

Please confirm the following details for our records. Note that this information will be stored separately from your survey.

Full name:
Address:
Suburb:
State:
Postcode:
Phone number:
Email address:
Full name of child enrolled in the Life on Holidays study:
Name of this Child's school:

Thank you for participating in this survey! The survey asks a range of questions about you and your household. It will take approximately 15 minutes to complete. Your responses are valuable, so please complete all the questions. Please be as honest as you can – your responses are completely confidential.

What is your age?	_____ years	Office use only Age_BL
What is you date of birth?	_____/_____/_____ (dd/mm/yyyy)	DOB_BL
What is your gender?		Gender_BL
	◯ Male	1
	◯ Female	2
	◯ Other	3
Are you of Aboriginal or Torres Strait Islander origin?		ASTI_BL
	◯ No	1
	◯ Yes, Aboriginal	2
	◯ Yes, Torres Strait Islander	3
	◯ Yes, Both Aboriginal and Torres Strait Islander	4
In which country were you born?		Country_BL
	◯ Australia	1
	◯ Other	2
If you selected "Other", please specify: _____		CountryOth_BL
What is your present marital status?		Marit_BL
	◯ Never married	1
	◯ Widowed	2
	◯ Divorced	3
	◯ Separated but not divorced	4
	◯ Married or de facto	5
How many adults live in your household (including yourself)? _____		HouseAdult_BL
How many children live in your household?	_____	HouseChild_BL

Office use only

What is your highest level of education completed? — Educ_BL

- ◯ Below year 10 — 1
- ◯ Year 10 — 2
- ◯ Year 11 — 3
- ◯ Year 12 or equivalent — 4
- ◯ Certificate III/IV — 5
- ◯ Advanced Diploma/Diploma — 6
- ◯ Bachelor degree — 7
- ◯ Postgraduate or higher degree — 8

What is the usual COMBINED gross income for your household (before taxes)? — Income_BL

- ◯ Less than $50,000 — 1
- ◯ Between $50,000 and $99,999 — 2
- ◯ Between $100,000 and $199,999 — 3
- ◯ Over $200,000 — 4

How many functioning motorised vehicles (car, motorcycle, moped, etc.) are available for use at your house? — Vehicles_BL

- ◯ 1 — 1
- ◯ 2 — 2
- ◯ 3 — 3
- ◯ 4 — 4
- ◯ 5 or more — 5

What best describes your type of television service for the primary television in the house? — TV_BL

- ◯ No television — 1
- ◯ Free-to-air (antenna only, no other service) — 2
- ◯ Paid television service (Satellite or cable service e.g. Foxtel, or internet streaming service e.g. Netflix, Stan, Apple TV). You may also have free-to-air service. — 3

Please indicate whether the following are <u>in your bedroom:</u>	(0) No	(1) Yes	
TV	◯	◯	BedAdult_TV_BL
Computer	◯	◯	BedAdult_Comp_BL
Video game system (non-hand held; PlayStation, Xbox, etc.)	◯	◯	BedAdult_Vid_BL

Now we would like to ask you some questions about your work.

How many hours per week on average do you work <u>outside the home</u>?

Office use only

Work_hr_BL

- ◯ None — 1
- ◯ Less than 15 hours per week — 2
- ◯ 15 to 35 hours per week — 3
- ◯ Full time (36+ hours per week) — 4

If you work <u>outside the home</u>, what is your occupation? _____ Work_Occ_BL

	(0) No	(1) Yes	(2) N/A (do not work outside the home)	
Do you work shift work that includes some night shifts?	◯	◯	◯	Work_Shift_BL
Do you regularly work on weekends?	◯	◯	◯	Work_Wkend_BL

The follow sections of the survey are about your health and well-being.

One hears about "morning-types" and "evening-types." Which one of these types do you consider yourself to be? Sleep_chronotype_BL

- ◯ Definitely a morning-type — 1
- ◯ Rather more a morning-type than an evening-type — 2
- ◯ Rather more an evening-type than a morning-type — 3
- ◯ Definitely an evening-type — 4

	(0) No	(1) Yes	(2) N/A	
Do you smoke?	◯	◯		Smoke_BL
If yes, do you smoke regularly, that is, at least once a day?	◯	◯	◯	Smoke_reg_BL

What is the least you have ever weighed (as an adult)? _____kg Weight_min_BL

What is the most you have ever weighed (as an adult, but do not include times you were pregnant)? _____kg Weight_max_BL

Has your weight been stable (within 5% of your body weight) in the last 3 months? For example, if you weigh 80kg, 5% of your body weight is 4kg. Therefore, your weight has been stable if it has not increased or decrease by more than 4kg.

Office use only
Weightstable_BL

- ◯ Yes, my weight has been stable — 1
- ◯ No, my weight has **increased** — 2
- ◯ No, my weight has **decreased** — 3

Do you consider yourself to be an acceptable weight, underweight or overweight?

Weightaccept_BL

- ◯ Acceptable weight — 1
- ◯ Underweight — 2
- ◯ Overweight — 3

Have you <u>ever been told</u> by a doctor or nurse that you have any of the following conditions?

	(0) No	(1) Yes	
Asthma	◯	◯	C_Asthma_BL
Any type of cancer	◯	◯	C_Cancer_BL
Any heart or circulatory conditions	◯	◯	C_Circ_BL
Gout, rheumatism or arthritis	◯	◯	C_Arth_BL
Osteoporosis or osteopenia	◯	◯	C_Osteo_BL
Diabetes	◯	◯	C_Diab_BL
Kidney disease	◯	◯	C_Kidney_BL
Affective (mood) or anxiety condition	◯	◯	C_Affect_BL
Mental health, behavioural or cognitive condition other than affective or anxiety condition	◯	◯	C_Mental_BL
Other condition	◯	◯	C_Other_BL
If you selected “Other condition”, please specify:			C_Specify_BL

These questions assess your tendencies towards routine. Please select the response that best matches how well each statement describes you.

	(1) Always	(2) Usually	(3) Sometimes	(4) Seldom	(5) Never	Office use only
In general, I like to do the same things each day.	◯	◯	◯	◯	◯	Routine1_BL
I like to wake up and go to bed at the same time each day.	◯	◯	◯	◯	◯	Routine2_ BL
I like to eat my meals at the same time each day.	◯	◯	◯	◯	◯	Routine3_ BL
I usually sit in the same seat when doing certain activities (for example: reading, watching TV, eating).	◯	◯	◯	◯	◯	Routine4_ BL
I usually put personal objects back in the same place each time I used them.	◯	◯	◯	◯	◯	Routine5_ BL
I like to plan my days out in advance.	◯	◯	◯	◯	◯	Routine6_ BL
Other people think I am “set in my ways”.	◯	◯	◯	◯	◯	Routine7_ BL
I think I am “set in my ways”.	◯	◯	◯	◯	◯	Routine8_ BL

Next, we'd like to ask you some questions about your child who is enrolled in the Life on Holidays study.

Please indicate your relationship to this child:

Office use only
ChRelat_BL

- ◯ Mother — 1
- ◯ Father — 2
- ◯ Step-mother — 3
- ◯ Step-father — 4
- ◯ Grandparent — 5
- ◯ Other guardian — 6

If you selected "Other guardian", please specify: ChRelat_Oth_BL

Think about your child who is enrolled in the Life on Holidays Study. Please indicate whether the following are in your child's bedroom:

	(0) No	(1) Yes	
TV	◯	◯	BedCh_TV_BL
Computer	◯	◯	BedCh_Comp_BL
Video game system (non-hand held; PlayStation, Xbox, etc.)	◯	◯	BedCh_Vid_BL

Think about your child who is enrolled in the Life on Holidays Study. During a typical week, how often do you or another adult in the household:

	(1) Never	(2) 1-2 days	(3) 3-4 days	(4) 5-6 days	(5) Every day	
Watch your child participate in physical activity or sports	◯	◯	◯	◯	◯	ChSport1_BL
Encourage your child to do sports or physical activity	◯	◯	◯	◯	◯	ChSport2_BL
Provide transport to a place where your child can do physical activity or play sports	◯	◯	◯	◯	◯	ChSport3_BL
Do a physical activity or play sports with your child	◯	◯	◯	◯	◯	ChSport4_BL

Mealtimes are different for different families. We are interested in what meals are like in your household. For each of the following items, please choose how often the statement describes meal times with your child and/or in your household. When answering the following questions, please think about your child who is enrolled in the Life on Holidays Study.

	(1) Never	(2) Rarely	(3) Sometimes	(4) Often	(5) Always or almost always	Office use only
My child eats meals with myself or other family members	○	○	○	○	○	Meal1_BL
The television is on in the same room when my child is eating meals	○	○	○	○	○	Meal2_BL
Our family eats an evening meal at a regular time	○	○	○	○	○	Meal3_BL
Meals in our household are rushed	○	○	○	○	○	Meal4_BL
We eat meals in the kitchen or dining room	○	○	○	○	○	Meal5_BL
We eat meals in the car	○	○	○	○	○	Meal6_BL
Everyone in our household eats something different at meals	○	○	○	○	○	Meal7_BL
At meals, my child eats the same food as everyone else	○	○	○	○	○	Meal8_BL
Someone in our household cooks meals	○	○	○	○	○	Meal9_BL
We say grace or have a ritual at the start of meals	○	○	○	○	○	Meal10_BL

Thinking about your child who is enrolled in the Life on Holidays Study, please indicate how often each of the following occurs.

	(1) Never/ almost never	(2) Rarely	(3) Sometimes	(4) Often	(5) Always/ almost always	Office use only
How often do you express affection by hugging, kissing and holding this child?	○	○	○	○	○	ParWarm1_BL
How often do you hug or hold this child for no particular reason?	○	○	○	○	○	ParWarm2_BL
How often do you tell this child how happy he/she makes you?	○	○	○	○	○	ParWarm3_BL
How often do you have warm, close times together with this child?	○	○	○	○	○	ParWarm4_BL
How often do you enjoy listening to this child and doing things with him/her?	○	○	○	○	○	ParWarm5_BL
How often do you feel close to this child both when he/she is happy and upset?	○	○	○	○	○	ParWarm6_BL
When you give this child an instruction or make a request to do something, how often do you make sure that he/she does it?	○	○	○	○	○	ParCont1_BL
If you tell this child he/she will get punished if he/she doesn't stop doing something, but he/she keeps doing it, how often will you punish him/her?	○	○	○	○	○	ParCont2_BL
How often does this child get away with things that you feel should have been punished?	○	○	○	○	○	ParCont3_BL
How often is this child able to get out of punishment when he/she really sets his/her mind to it?	○	○	○	○	○	ParCont4_BL
When you discipline this child, how often does he/she ignore the punishment?	○	○	○	○	○	ParCont5_BL

Thank you for completing the survey!

We are grateful for your valuable contribution.

ONLINE SURVEY – FIRST DECEMBER SURVEY (T1)

Welcome to the baseline survey for the ARIA study. This will be the first of 8 surveys you will be asked to complete across the 12-month study period.

This survey asks a range of questions about your activities, health and wellbeing. It will take approximately 10-15 minutes to complete. Please complete all the questions in one sitting.

We ask that you complete this survey as honestly and completely as you can. Your responses are valuable. There are no right or wrong answers, and your responses will be kept confidential.

Thank you again for your time and commitment to the study.

Kind regards, the ARIA study team.

Work_hr_T1	How many hours per week on average do you work outside the home?	
	◯ None	(1)
	◯ Less than 15 hours per week	(2)
	◯ 15 to 35 hours per week	(3)
	◯ Full time (36+ hours per week)	(4)

Holidays_T1	Have you been on holidays or had annual leave in the past month?	
	◯ Yes	(1)
	◯ No	(2)

	Please indicate on which days you have had holidays or annual leave in the past month. You can enter up to 4 separate occasions of leave.
Holidays1S_T1	Leave/holiday 1: Start Date
Holidays1E_T1	Leave/holiday 1: End Date
Holidays2S_T1	Leave/holiday 2: Start Date
Holidays2E_T1	Leave/holiday 2: End Date
Holidays3S_T1	Leave/holiday 3: Start Date
Holidays3E_T1	Leave/holiday 3: End Date
Holidays4S_T1	Leave/holiday 4: Start Date
Holidays4E_T1	Leave/holiday 4: End Date

Away_T1	During any of the above periods, did you go away from home?	
	◯ Yes	(1)
	◯ No	(2)

	If yes, please indicate on which days you went away from home.
Away1S_T1	Away 1: Start Date
Away1E_T1	Away 1: End Date
Away2S_T1	Away 2: Start Date
Away2E_T1	Away 2: End Date
Away3S_T1	Away 3: Start Date
Away3E_T1	Away 3: End Date
Away4S_T1	Away 4: Start Date
Away4E_T1	Away 4: End Date

HolidayAct_T1	What was your main activity while you were on holidays or annual leave? Please provide a response even if you did not go away from home. <open-ended response >

The follow sections of the survey are about your health and well-being.

	We are interested in how and why adults' weight changes over time. In some cases, taking medication can affect weight. Are you currently taking any of the following medications?	(1) Yes	(2) No
Medication1_T1	**Antipsychotic medicines**, such as olanzapine, risperidone, haloperidol	◯	◯
Medication2_T1	**Antidepressant medicines**, such as amitriptyline, fluoxetine, phenelzine	◯	◯
Medication3_T1	**Anticonvulsant medicines** (medication for epilepsy), such as gabapentin, valproate, carbamazepine	◯	◯
Medication4_T1	**Medicines for diabetes**, such as insulin, sulfonylureas, meglitinides, metformin	◯	◯
Medication5_T1	**Steroid or hormone medicines**, such as cortisone, prednisone, hormonal contraceptives (e.g. oral or injections), hormone replacement therapy	◯	◯
Medication6_T1	**Medicines for blood pressure**, such as beta-blockers (e.g. propranolol), alpha-blockers (e.g. clonidine), diuretics	◯	◯

		(1) Yes	(2) No
LoseMaintainWeight_T1	In the past month, have you tried to lose weight or maintain your weight (that is, prevent weight gain)?	◯	◯

WhichWeight_T1	Which better describes your past month?	
	◯ I have tried to lose weight	(1)
	◯ I have tried to maintain my weight (prevent weight gain)	(2)

	We'd like to ask you about some specific strategies you might have used to lose weight or maintain your weight in the past month:	(1) Yes	(2) No
Weightstrategy1_T1	Have you restricted calories?	◯	◯
Weightstrategy2_T1	Have you counted calories?	◯	◯
Weightstrategy3_T1	Have you exercised or been physically active?	◯	◯
Weightstrategy4_T1	Have you taken diet pills to decrease appetite?	◯	◯
Weightstrategy5_T1	Have you used special products such as powdered supplements?	◯	◯
Weightstrategy6_T1	Have you fasted?	◯	◯
Weightstrategy7_T1	Have you caused yourself to vomit after you eat?	◯	◯
Weightstrategy8_T1	Is there anything else you have done to lose or maintain your weight?	◯	◯

OtherWeightstrategy_T1	If you answered yes to the last item above (is there anything else you have done to lose weight?) please describe here:

This next section asks how you feel about your quality of life, health, or other areas of your life. Please answer all the questions. If you are unsure about which response to give to a question, please choose the one that appears most appropriate. This can often be your first response.

Please keep in mind your standards, hopes, pleasures and concerns. We ask that you think about your life in the past month.

		Very poor	Poor	Neither poor nor good	Good	Very good
		1	2	3	4	5
WHOQOL1_T1	How would you rate your quality of life?	◯	◯	◯	◯	◯

		Very dissatisfied	Dissatisfied	Neither satisfied nor dissatisfied	Satisfied	Very satisfied
		1	2	3	4	5
WHOQOL2_T1	How satisfied are you with your health?	◯	◯	◯	◯	◯

The following questions ask about **how much** you have experienced certain things in the past month.

		Not at all	A little	A moderate amount	Very much	An extreme amount
		1	2	3	4	5
WHOQOL3_T1	To what extent do you feel that physical pain prevents you from doing what you need to do?	◯	◯	◯	◯	◯
WHOQOL4_T1	How much do you need any medical treatment to function in your daily life?	◯	◯	◯	◯	◯
WHOQOL5_T1	How much do you enjoy life?	◯	◯	◯	◯	◯
WHOQOL 6_T1	To what extent do you feel your life to be meaningful?	◯	◯	◯	◯	◯

		Not at all	A little	A moderate amount	Very much	Extremely
		1	2	3	4	5
WHOQOL 7_T1	How well are you able to concentrate?	○	○	○	○	○
WHOQOL 8_T1	How safe do you feel in your daily life?	○	○	○	○	○
WHOQOL 9_T1	How healthy is your physical environment?	○	○	○	○	○

The following questions ask about **how completely** you experienced or were able to do certain things in the past month.

		Not at all	Not much	Moderately	Mostly	Completely
		1	2	3	4	5
WHOQOL 10_T1	Do you have enough energy for everyday life?	○	○	○	○	○
WHOQOL 11_T1	Are you able to accept your bodily appearance?	○	○	○	○	○
WHOQOL 12_T1	Have you enough money to meet your needs?	○	○	○	○	○
WHOQOL 13_T1	How available to you is the information that you need in your day-to-day life?	○	○	○	○	○
WHOQOL 14_T1	To what extent do you have the opportunity for leisure activities?	○	○	○	○	○

		Very poor	Poor	Neither poor or good	Good	Very good
		1	2	3	4	5
WHOQOL 15_T1	In the past month, how well were you able to get around?	○	○	○	○	○

The following questions ask you to say how **good or satisfied** you have felt about various aspects of your life over the past month.

		Very dissatisfied	Dissatisfied	Neither satisfied nor dissatisfied	Satisfied	Very satisfied
		1	2	3	4	5
WHOQOL 16_T1	How satisfied are you with your sleep?	○	○	○	○	○
WHOQOL 17_T1	How satisfied are you with your ability to perform your daily living activities?	○	○	○	○	○
WHOQOL 18_T1	How satisfied are you with your capacity for work?	○	○	○	○	○
WHOQOL 19_T1	How satisfied are you with yourself?	○	○	○	○	○
WHOQOL 20_T1	How satisfied are you with your personal relationships?	○	○	○	○	○
WHOQOL 21_T1	How satisfied are you with your sex life?	○	○	○	○	○
WHOQOL 22_T1	How satisfied are you with the support you get from your friends?	○	○	○	○	○
WHOQOL 23_T1	How satisfied are you with the conditions of your living place?	○	○	○	○	○
WHOQOL 24_T1	How satisfied are you with your access to health services?	○	○	○	○	○
WHOQOL 25_T1	How satisfied are you with your transport?	○	○	○	○	○

The following question refers to **how often** you have felt or experienced certain things in the past month.

		Never	Seldom	Quite often	Very often	Always
		1	2	3	4	5
WHOQOL 26_T1	How often do you have negative feelings such as blue mood, despair, anxiety, depression?	○	○	○	○	○

		Not at all	A little	A moderate amount	Very much	Extremely
		1	2	3	4	5
Hap_T1	Thinking about the past month, in general, how happy are you?	○	○	○	○	○

Please read each statement and indicate how much it applied to you ***over the past month***.

		Did not apply to me at all	Applied to me to some degree, or some of the time	Applied to me to a considerable degree, or a good part of time	Applied to me very much, or most of the time
		1	2	3	4
DASS1_T1	I found it hard to wind down	○	○	○	○
DASS2_T1	I was aware of dryness of my mouth	○	○	○	○
DASS3_T1	I couldn't seem to experience any positive feeling at all	○	○	○	○
DASS4_T1	I experienced breathing difficulty (eg, excessively rapid breathing, breathlessness in the absence of physical exertion)	○	○	○	○
DASS5_T1	I found it difficult to work up the initiative to do things	○	○	○	○
DASS6_T1	I tended to over-react to situations	○	○	○	○
DASS7_T1	I experienced trembling (eg, in the hands)	○	○	○	○
DASS8_T1	I felt that I was using a lot of nervous energy	○	○	○	○
DASS9_T1	I was worried about situations in which I might panic and make a fool of myself	○	○	○	○
DASS10_T1	I felt that I had nothing to look forward to	○	○	○	○
DASS11_T1	I found myself getting agitated	○	○	○	○
DASS12_T1	I found it difficult to relax	○	○	○	○
DASS13_T1	I felt down-hearted and blue	○	○	○	○
DASS14_T1	I was intolerant of anything that kept me from getting on with what I was doing	○	○	○	○
DASS15_T1	I felt I was close to panic	○	○	○	○
DASS16_T1	I was unable to become enthusiastic about anything	○	○	○	○
DASS17_T1	I felt I wasn't worth much as a person	○	○	○	○
DASS18_T1	I felt that I was rather touchy	○	○	○	○
DASS19_T1	I was aware of the action of my heart in the absence of physical exertion (e.g., sense of heart rate increase, heart missing a beat)	○	○	○	○
DASS20_T1	I felt scared without any good reason	○	○	○	○
DASS21_T1	I felt that life was meaningless	○	○	○	○

	How often have you done these recreational activities in the past month?	Never	Once a month	Once every 2 weeks	Once a week	More than once a week
		1	2	3	4	5
Rec1_T1	Physical activity with others in a park (e.g. frisbee, games)	○	○	○	○	○
Rec2_T1	Running or jogging	○	○	○	○	○
Rec3_T1	Weights	○	○	○	○	○
Rec4_T1	Cycling	○	○	○	○	○
Rec5_T1	Exercise class (e.g. aerobics)	○	○	○	○	○
Rec6_T1	Golf	○	○	○	○	○
Rec7_T1	Swimming	○	○	○	○	○
Rec8_T1	Tennis	○	○	○	○	○
Rec9_T1	Team sports (e.g. football, netball, hockey, softball)	○	○	○	○	○
Rec10_T1	Yoga, pilates, tai chi or qigong	○	○	○	○	○
Rec11_T1	Lawn bowls	○	○	○	○	○
Rec12_T1	Home-based exercises (e.g. stretches, fitball, workout video)	○	○	○	○	○
Rec13_T1	Boating/sailing	○	○	○	○	○
Rec14_T1	Water activities (e.g. rowing, diving, canoeing)	○	○	○	○	○
Rec15_T1	Physical activity with others on a beach (e.g. frisbee, games)	○	○	○	○	○

ScreenWD_T1	In the past month, how many hours did you usually watch television or use an electronic device (computer, tablet, smartphone, video games) in your free time on a weekday? <number only>
ScreenWE_T1	In the past month, how many hours did you usually watch television or use an electronic device (computer, tablet, smartphone, video games) in your free time on a weekend day? <number only>

These questions assess your tendencies towards routine. Please select the response that best matches how well each statement describes you.

		Always	Usually	Sometimes	Seldom	Never
		1	2	3	4	5
Routine1_T1	In general, I like to do the same things each day.					
Routine2_T1	I like to wake up and go to bed at the same time each day.					
Routine3_T1	I like to eat my meals at the same time each day.					
Routine4_T1	I usually sit in the same seat when doing certain activities (for example: reading, watching TV, eating).					
Routine5_T1	I usually put personal objects back in the same place each time I used them.					
Routine6_T1	I like to plan my days out in advance.					
Routine7_T1	Other people think I am "set in my ways".					
Routine8_T1	I think I am "set in my ways".					

Survey Complete!

Thank you for completing this detailed survey, your time is greatly appreciated. If you have not already done so, please also complete the food frequency questionnaire. The link to complete the food frequency questionnaire is in the same email which contained the link to this survey.

University of South Australia

Statement of Authorship

Title of Paper	The annual rhythms in sleep, sedentary behavior and physical activity of Australian adults: a prospective cohort study
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Contribution to the Paper Brief description of your work in this publication	I led or contributed across all stages of this paper.	
Overall Percentage (%)	35	
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CO-AUTHOR CONTRIBUTIONS

By signing the Statement of Authorship, each author certifies that:

I. the candidate's stated contribution to the publication is accurate (as detailed above);

II. permission is granted for the candidate in include the publication in the thesis; and

III. the sum of all co-author contribution is equal to 100% less the candidate's stated contribution.

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Appendix A4.2 – Table of day of the week comparisons

	Day of the week			
		Coefficient	[95% CI]	p
Sleep	Monday (cons)	489.4	[484.4, 494.4]	
	Tuesday	**-7.5**	[-9.3, -5.7]	<0.001
	Wednesday	**-11.1**	[-12.9, -9.3]	<0.001
	Thursday	**-11.6**	[-13.4, -9.8]	<0.001
	Friday	**-19.3**	[-21.1, -17.5]	<0.001
	Saturday	**17.9**	[16.1, 19.8]	<0.001
	Sunday	**46.6**	[44.8, 48.4]	<0.001
Sedentary	Monday (cons)	623.9	[616.2, 631.6]	
	Tuesday	**7.9**	[5.6, 10.1]	<0.001
	Wednesday	**8.5**	[6.2, 10.7]	<0.001
	Thursday	**4.3**	[2.0, 6.5]	<0.001
	Friday	**7**	[4.7, 9.3]	<0.001
	Saturday	**-38.2**	[-40.5, -35.9]	<0.001
	Sunday	**-51.2**	[-53.5, -48.9]	<0.001
LPA	Monday (cons)	297.6	[291.0, 304.2]	
	Tuesday	-0.8	[-2.4, 0.9]	0.356
	Wednesday	**1.8**	[0.1, 3.4]	0.037
	Thursday	**5.8**	[4.2, 7.5]	<0.001
	Friday	**12.2**	[10.6, 13.9]	<0.001
	Saturday	**14.1**	[12.4, 15.8]	<0.001
	Sunday	0.4	[-1.3, 2.1]	0.663
MVPA	Monday (cons)	31.6	[29.4, 33.9]	
	Tuesday	0.6	[-0.1, 1.4]	0.113
	Wednesday	0.6	[-0.1, 1.4]	0.105
	Thursday	**1.1**	[0.3, 1.9]	0.006
	Friday	0.3	[-0.5, 1.1]	0.483
	Saturday	**5.6**	[4.8, 6.4]	<0.001
	Sunday	**3.8**	[3.0, 4.6]	<0.001

Notes: Bold values indicate p<0.05. CI = confidence interval, cons = constant, LPA = light physical activity, MVPA = moderate-to-vigorous physical activity.

Appendix A4.3 – Table of seasonal comparisons

	Season			
		Coefficient	[95% CI]	p
Sleep	Summer (cons)	492.8	[487.7, 498.0]	
	Autumn	**4.4**	[1.8, 7.0]	0.001
	Winter	**10.7**	[8.1, 13.3]	<0.001
	Spring	0.9	[-1.8, 3.5]	0.518
Sedentary	Summer (cons)	612.2	[601.5, 622.9]	
	Autumn	2.2	[-1.0, 5.4]	0.178
	Winter	**6.5**	[3.3, 9.8]	<0.001
	Spring	-0.9	[-4.2, 2.4]	0.581
LPA	Summer (cons)	301.2	[294.5, 307.8]	
	Autumn	**-6**	[-8.2, -3.7]	<0.001
	Winter	**-14.8**	[-17.1, -12.5]	<0.001
	Spring	-0.8	[-3.1, -1.6]	0.52
MVPA	Summer (cons)	33.6	[31.2, 35.9]	
	Autumn	-0.3	[-1.3, 0.8]	0.615
	Winter	**-2.2**	[-3.3, -1.2]	<0.001
	Spring	**1.5**	[0.4, 2.5]	0.008

Notes: Bold values indicate p<0.05. CI = confidence interval, cons = constant, LPA = light physical activity, MVPA = moderate-to-vigorous physical activity.

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RESEARCH

Open Access

Weather associations with physical activity, sedentary behaviour and sleep patterns of Australian adults: a longitudinal study with implications for climate change

Ty Ferguson[1*], Rachel Curtis[1], Francois Fraysse[1], Timothy Olds[1], Dorothea Dumuid[1], Wendy Brown[2], Adrian Esterman[1] and Carol Maher[1]

Abstract

Background Weather is a potentially important influence on how time is allocated to sleep, sedentary behaviour and physical activity across the 24-h day. Extremes of weather (very hot, cold, windy or wet) can create undesirable, unsafe outdoor environments for exercise or active transport, impact the comfort of sleeping environments, and increase time indoors. This 13-month prospective cohort study explored associations between weather and 24-h movement behaviour patterns.

Methods Three hundred sixty-eight adults (mean age 40.2 years, SD 5.9, 56.8% female) from Adelaide, Australia, wore Fitbit Charge 3 activity trackers 24 h a day for 13 months with minute-by-minute data on sleep, sedentary behaviour, light physical activity (LPA), and moderate-to-vigorous physical activity (MVPA) collected remotely. Daily weather data included temperature, rainfall, wind, cloud and sunshine. Multi-level mixed-effects linear regression analyses (one model per outcome) were used.

Results Ninety thousand eight hundred one days of data were analysed. Sleep was negatively associated with minimum temperature (-12 min/day change across minimum temperature range of 31.2 °C, $p = 0.001$). Sedentary behaviour was positively associated with minimum temperature (+12 min/day, range = 31.2 oC, $p = 0.006$) and wind speed (+10 min/day, range = 36.7 km/h, $p < 0.001$), and negatively associated with sunshine (-17 min/day, range = 13.9 h, $p < 0.001$). LPA was positively associated with minimum temperature (+11 min/day, range = 31.2 °C, $p = 0.002$), cloud cover (+4 min/day, range = 8 eighths, $p = 0.008$) and sunshine (+17 min/day, range = 13.9 h, $p < 0.001$), and negatively associated with wind speed (-8 min/day, range = 36.7 km/h, $p < 0.001$). MVPA was positively associated with sunshine (+3 min/day, range = 13.9 h, $p < 0.001$) and negatively associated with minimum temperature (-13 min/day, range = 31.2 oC, $p < 0.001$), rainfall (-3 min/day, range = 33.2 mm, $p = 0.006$) and wind speed (-4 min/day, range = 36.7 km/h, $p < 0.001$). For maximum temperature, a significant ($p < 0.05$) curvilinear association was observed with sleep (half-U) and physical activity (inverted-U), where the decrease in sleep duration appeared to slow around 23 °C, LPA peaked at 31 oC and MVPA at 27 °C.

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Conclusions Generally, adults tended to be less active and more sedentary during extremes of weather and sleep less as temperatures rise. These findings have the potential to inform the timing and content of positive movement behaviour messaging and interventions.

Trial registration The study was prospectively registered on the Australian New Zealand Clinical Trial Registry (Trial ID: ACTRN12619001430123).

Keywords Physical activity, Sedentary behaviour, Sleep, Weather, Movement behaviours, 24-h day, Time use, Temperature, Rainfall, Wind speed

Introduction

At any time of the day, a person is engaged in one of three movement behaviours; sleeping, being sedentary, or being active [1]. The relative distribution of these behaviours has impacts on health. Insufficient physical activity or sleep, and excess sleep or sedentary behaviour are associated with poor health outcomes, including increased risk of chronic illness and reduced life expectancy [2–5]. When considering day-to-day changes in movement behaviours, each is intrinsically linked, whereby changes in one behaviour result in equal and opposite changes across the remaining behaviours [6]. The time allocated to each behaviour in a 24-h day is influenced by both internal factors such as motivation, fatigue, and physical health, and external factors, including work or family commitments, physical environment, resource availability and the weather [7–9].

The weather we experience each day is the result of a complex and ever-changing system of atmospheric variables [10]. Weather conditions can either afford or limit opportunities to participate in movement behaviours. This may be directly, for example through impacting thermoregulation, [11] or indirectly by changing the usability and safety of the physical environment [12]. Whilst weather is not an acutely modifiable factor, understanding its association with movement behaviours is valuable for identifying potential conditions where less favourable movement behaviour patterns occur.

Extremes of weather (i.e. too hot, cold, windy or wet) reduces mobility and engagement with our physical environment [12, 13]. This may limit opportunities for physical activity, including outdoor exercise, recreation, and safe active transport, reduce the comfort of sleeping environments, and more time may be spent indoors where sedentary pursuits are common (i.e. sitting, watching TV, using computers and mobile devices) [14]. Current literature suggests that in general adults sleep less as temperatures rise, are more sedentary when rainfall is higher or temperatures are lower, and are less active during extremes of temperature, and during higher rainfall and wind speeds [15–19]. There is currently no clear association between movement behaviours and cloud cover or daily sunlight volume. The direction of the associations are more generalisable than specific magnitudes, as weather is regionally specific [15]. Weather patterns are influenced by a region's distance from the equator, daylight hours, height above sea level, topography and proximity to the ocean [20].

There are several limitations to the current body of evidence for weather-based research. Broadly, a large portion of studies has focused on seasonal changes, which provides only a low-resolution comparison of weather conditions in specific timepoints across the year [15]. Additionally, studies have mostly used cross-sectional designs with subjectively measured movement behaviours, and often explore movement behaviours in isolation, e.g. physical activity only [15]. To our knowledge, no studies anywhere in the world have used a longitudinal design over a full 12-month seasonal cycle, to capture 24-h movement behaviour. The current study aims to fill these gaps by exploring the associations between weather conditions (maximum temperature, minimum temperature, rainfall, wind speed, cloud cover and sunshine) and daily device-measured movement behaviours (sleep, sedentary behaviour, light physical activity and moderate-to-vigorous physical activity) and to comment on how these associations fit with climate change projections. The findings may assist with the timing and design of movement behaviour interventions.

Methods

Study design

Data collected from the *Annual Rhythms In Adults' lifestyle and health* (ARIA) prospective cohort study were used in this analysis. ARIA collected data on body weight, 24-h movement behaviours, dietary patterns and well-being in a cohort of Australian adults over a 13-month period. Further details of the study protocol have been published elsewhere [21].

Ethics approval was provided by the University of South Australia Human Research Ethics committee (Protocol number: 201901). The study was prospectively registered on the Australian New Zealand Clinical Trial Registry (Trial ID: ACTRN12619001430123).

Setting and participants

Three hundred seventy-five community-based adults were recruited from the greater metropolitan area of Adelaide, South Australia for the ARIA study. They were recruited in two ways: (1) parents of children enrolled in a separate cohort study called *Life on Holidays* [22] (cohorts 1 and 2), or (2) parents of primary school children recruited from the community through general advertising (i.e. social media posts, paid digital advertisements, community notice boards) (cohort 3).

Enrolment occurred in two waves: cohort 1 participants commenced on 1st December 2019, cohorts 2 and 3 commenced on 1st December 2020. Each wave remained in the study until the end of the following December (31st December 2020 and 31st December 2021 respectively), totalling 13 months in the study.

Inclusion criteria were: age 18 to 65 years; a parent/guardian of a child enrolled in Life on Holidays study or a parent/guardian of child aged 5 to 12 years; residing in the greater metropolitan Adelaide area; having access to a Bluetooth-enabled mobile phone or computer and home internet; being proficient in English; and being ambulant. Exclusion criteria were: being pregnant; having an implanted electronic medical device; or receiving treatment for, or experiencing, any life-threatening condition which impacted daily lifestyle and health.

A researcher visited each eligible and consenting participant at their home between August and November in the year of commencing the study. At this visit baseline height was measured and participants completed a baseline survey containing demographic, health and lifestyle items. Participants were provided with a Fitbit Charge 3 fitness tracker and Fitbit Aria body weight scale (Aria 2 or Aria Air scale, Fitbit Inc., San Francisco, CA, USA).

During the study period, participants used the Fitbit devices daily and completed eight follow-up surveys of wellbeing and diet (not used in the current analysis). Participants did not require any face-to-face session after the baseline visit, unless technical support was required. On completion of the study, participants received an honorarium of $100 and were able to keep the Fitbit Charge 3 and Aria scale.

Variables

Daily movement behaviour patterns

Device-measured minute-by-minute movement behaviour data were collected using a wrist-worn Fitbit Charge 3 activity tracker (Fitbit Inc., San Francisco, CA, USA). The device was worn on the participants' non-dominant wrist, 24 h a day (except whilst charging or during water activities). Participants were asked to sync data to the linked Fitbit user account frequently (at least every 5 days), so that data could be collected remotely via purpose-built software called "Fitnesslink" (Portal Australia, Adelaide, Australia).

Each minute was classified as either sleep, sedentary behaviour, light physical activity, moderate or vigorous physical activity, or non-wear time, using Fitbit's proprietary algorithm. Fitbit devices have shown acceptable validity for sleep duration (compared to polysomnography: Charge 2 sensitivity = 0.96, specificity = 0.61; [23] Flex $r = 0.97$ [24]), sedentary behaviour (compared to ActivPAL: Charge 3 ICC = 0.94 (95% CI: 0.92–0.96 [25])) and moderate-to-vigorous physical activity (compared to Actigraph: Charge 2 ICC = 0.69 (95% CI: 0.35–0.87) [26], Flex $r = 0.73$ [27]).

Weather

Adelaide is the capital city of South Australia with a population of approximately 1.4 million people. The metropolitan area is situated on a western coastline with flat plains extending toward steep hills in the eastern and southern regions (34° latitude and 138° longitude) [28]. Adelaide's climate is considered temperate (Köppen classification), [29] and is characterised by four distinct seasons, including cold, wet winters and warm, dry, low humidity summers [30]. Average weather data during the study are summarised in Table 1. Daily weather data for Adelaide were collected from the Australian Data Archive for Meteorology [31]. Weather variables were reported as the average of data from five major weather stations spread geographically across the Adelaide metropolitan area. Maximum temperature (°C), minimum temperature (°C), rainfall (mm) and sunshine (defined as "bright" sunshine, which is less than the amount of visible sunlight per day, e.g. sunrise and sunset would be below the threshold for "bright" sunshine) [32] were reported as a single daily value. Wind speed (km/h) was reported as maximum gust, and at 9am and 3 pm daily, with an average of the three values used to derive an overall daily value. Relative humidity (%) and cloud cover (eighths) were reported twice daily (9am and 3 pm) with an average of the two used to derive an overall daily value. Average temperature (°C) was calculated as the mean of maximum and minimum temperatures. Apparent temperature (°C) was calculated using the Steadman formula [33] incorporating average temperature, humidity, wind speed and atmospheric pressure (hPa).

Demographic characteristics

At baseline, participants reported their sex, date of birth, marital status, number of children in household, smoking status, presence of chronic conditions, highest education level, combined gross household income and hours of work per week outside the home. They also self-reported

Table 1 Average monthly weather during study period

	Summer			Autumn			Winter			Spring		
	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Daily min temp (°C)	14.3	15.6	15.0	13.8	11.5	9.2	7.7	6.6	7.4	9.5	10.2	12.9
Daily max temp (°C)	27.0	27.9	25.7	24.8	21.2	17.2	15.1	14.2	15.1	18.9	20.4	24.8
Total rainfall (mm)	11.0	27.9	34.1	11.1	58.4	50.6	99.8	65.9	55.3	53.2	62.1	29.5
Daily windspeed (km/h)	24.4	23.7	22.6	22.2	20.6	21.9	21.4	22.7	23.1	25.7	23.8	24.4
Daily sunshine (hr)	10.5	10.2	9.5	8.6	7.1	5.3	5.0	5.1	6.6	7.4	7.8	9.2
Daily cloud cover (/8)	3.4	3.6	3.8	4.1	4.3	5.4	5.4	5.3	4.6	4.6	4.7	4.5
Relative humidity (%)	45.3	46.2	53.7	51.9	58.6	62.8	73.8	74.0	70.1	60.3	58.7	49.1

Colour gradient represents lowest month (darkest blue) to highest month (darkest orange) for each variable. Each column is the average of the years over which the study was conducted, i.e. January to November columns are the average of 2020 and 2021, and December is the average of 2019, 2020 and 2021

Max Maximum, *min* Minimum, *temp* Temperature

their sleep chronotype using a single-item from the Morningness-Eveningness questionnaire [34].

Statistical analysis

Daily total minutes of sleep, sedentary behaviour, light physical activity and moderate-to-vigorous physical activity were calculated for each participant day. A valid day was defined as 18 h or more of wear-time including a period of sleep. Moderate-to-vigorous physical activity was calculated as the sum of moderate physical activity and vigorous physical activity daily totals. Days on which a participant reported being away from home on vacation were excluded from analyses. Participants were included if they had at least 2 valid days of data to ensure repeat measurement.

Prior to performing the primary statistical analyses, independent weather variables were compared for collinearity (Table 2). Where a high correlation (≥ 0.80) was present, only one of the paired variables was included in the primary analyses. Specifically, maximum temperature was retained as it was the only common variable across all high correlation pairings. Six weather variables were retained from the original nine, these were minimum temperature, maximum temperature, rainfall, wind speed, sunshine and cloud cover.

Independent vs dependent variable scatterplots of raw data were generated in R version 4.1.3 (R Foundation for

Table 2 Pearson correlation coefficients between weather variables

	Min temp	*Max temp*	*Avg temp*	*App temp*	*Rainfall*	*Sunshine*	*Humidity*	*Wind speed*	*Cloud cover*
Min temp									
Max temp	0.77								
Avg temp	**0.92**	**0 96**							
App temp	**0.90**	**0 93**	**0.97**						
Rainfall	-0.11	-0.31	-0.24	-0.24					
Sunshine	0.11	0.48	0.35	0.32	-0.22				
Humidity	-0.49	**-0.82**	-0.73	-0.61	0.39	-0.50			
Wind speed	0.22	-0.03	0.07	-0.11	0.22	-0.10	-0.04		
Cloud cover	-0.03	-0.38	-0.25	-0.23	0.20	-0.78	0.44	0.18	

Bold indicates a high correlation ($\geq \pm 0.80$)

Avg Average, *app* Apparent, *max* Maximum, *min* Minimum, *temp* Temperature

Statistical Computing, Vienna, Austria) and presented as smoothing lines with 95% confidence intervals using generalised linear models for linear relationships and generalised additive models for quadratic relationships. A quadratic relationship was observed between maximum temperature and movement behaviour variables; to account for this relationship a variable of maximum temperature squared was included in the analyses.

Multi-level mixed-effects linear regression analyses were performed using Stata 17 (StataCorp, College Station, TX, USA) with statistical significance set at 0.05. Multilevel modelling with random intercepts was used to adjust for the non-independence of the data and to account for nesting of repeated measures within individuals, individuals within families, and families within waves. The movement behaviours were the dependent variables (one per model). The weather variables were included as fixed effects (all included in the same model). The regression coefficients for the weather variables were used to identify the difference in daily minutes of movement behaviours associated with an increase of one degree of temperature, one millimetre of rainfall, one kilometre per hour of wind speed, an eighth of cloud cover, and one minute of sunshine.

Results

Participants

Movement behaviour data were available for 368 of the initial 375 enrolled (see Table 3). Participants were predominantly mid-aged (mean = 40 years [SD = 6 years], range = 27 to 65 years), overweight or obese (34% and 35% respectively), married or in de facto relationships (85%), and had two or more children in their household (90%). Almost half the participants were educated to university level (48%), worked full time equivalent hours (46%), worked in managerial or professional occupations (40%) and had a household income between $100,000 and $200,000 (48%).

Movement behaviour data

Data from 90,801 valid days were analysed, with an average of 247 (SD = 113) valid days per participant (see Supplementary Fig. 1 for distribution of valid days per participant). On a day-by-day basis, the average percentage of participants with valid data was 64% (SD = 6.6%) with the daily percentage declining gradually over the 13-month study period (first month = 73%, thirteenth month = 51%). Across all valid days, participants' daily averages for movement behaviours were 8 h and 10 min of sleep (SD = 89 min), 10 h and 19 min of sedentary behaviour (SD = 120 min), 4 h and 59 min of light physical activity (SD = 93 min) and 32 min of moderate-to-vigorous physical activity (SD = 38 min).

Table 3 Participant demographics ($n = 368$)

	Mean	(SD)
Age (years)	40.2	(5.9)
Weight (kg)	84.0	(20.5)
Height (cm)	170.4	(9.5)
	N	**(%)**
Sex		
Female	209	(56.8)
Male	159	(43.2)
Weight status		
Underweight	1	(0.3)
Normal	114	(31.0)
Overweight	124	(33.7)
Obese	129	(35.1)
Smoker	34	(9.2)
Aboriginal and Torres Strait Islander peoples	4	(1.1)
Born in Australia	279	(75.8)
Marital status		
Never married	26	(7.1)
Married/de facto	313	(85.1)
Separated, divorced or widowed	29	(7.8)
Chronic illness		
None	163	(44.3)
Single	107	(29.1)
Multiple	98	(26.6)
Self-reported sleep chronotype		
Definitely a morning type	82	(22.3)
More a morning type than evening type	122	(33.2)
More an evening type than morning type	111	(30.2)
Definitely an evening type	53	(14.4)
Adults in household		
One	38	(10.3)
Two	305	(82.9)
Three	17	(4.6)
Four or more	7	(1.9)
Children in household		
One	36	(9.8)
Two	195	(53.0)
Three	95	(25.8)
Four or more	42	(11.5)
Education		
Year 10 or less	17	(4.6)
Year 11—12	49	(13.3)
Certificate/Diploma	125	(34.0)
University degree	177	(48.1)
Occupation		
Managerial and professional	148	(40.2)
Technical and clerical	77	(20.9)
Community, personal service, sales	67	(18.2)
Machinery operators, drivers, labourers	14	(3.8)
No job/other	62	(16.8)

Table 3 (continued)

	Mean	(SD)
Household income (Australian dollars)		
< $50,000	37	(10.1)
Between $50,000 and $99,999	111	(30.2)
Between $100,000 and $199,999	176	(47.8)
≥ $200,000	44	(12.0)
None	55	(14.9)
< 15	25	(6.8)
15–35	119	(32.3)
36 +	169	(45.9)

Associations between weather and movement behaviours

The relationships between temperature (maximum and minimum) and observed raw movement behaviour data are shown in Fig. 1. For maximum temperature, the non-linear relationship is represented using generalised additive models for line fitting. Notably, both light physical activity and moderate-to-vigorous physical activity increase with temperature from 9 oC towards a peak at approximately 31 oC and 27 oC respectively, before decreasing as temperature increases to the upper limit of 44 oC. The optimal 10 oC range for maximum temperature appears to be 25–35 oC for light physical activity and 22–32 oC for moderate-to-vigorous physical activity, giving an overlap of 25–32 oC for both activity types to be optimised.

Results of multi-level mixed-effects linear regression analyses are presented in Table 4. Sleep, light physical activity and moderate-to-vigorous physical activity were all associated with both maximum temperature and maximum temperature squared, suggesting a curvilinear relationship. Sleep was also negatively associated with minimum temperature (-12 min/day change across minimum temperature range of 31.2 °C). Sedentary behaviour was positively associated with minimum temperature and wind speed (+ 12 min/day, range = 31.2 °C and + 10 min/day, range = 36.7 km/h respectively), and negatively associated with sunshine (-17 min/day, range = 13.9 h). Light physical activity was positively associated with minimum temperature (+ 11 min/day, range = 31.2 oC), cloud cover (+ 4 min/day, range = 8 eighths) and sunshine (+ 17 min/day, range = 13.9 h), and negatively associated with wind speed (-8 min/day, range = 36.7 km/h). Moderate-to-vigorous physical activity was positively associated with sunshine (+ 3 min/day, range = 13.9 h), and negatively associated with minimum temperature (-13 min/day, range = 31.2 oC), rainfall (-3 min/day, range = 33.2 mm), and wind speed (-4 min/day, range = 36.7 km/h).

Discussion

This study explored the associations between daily weather conditions and device-measured movement behaviours using longitudinal data across a 13-month period. Several significant associations were observed. Sleep was inversely associated with minimum temperature, sedentary behaviour was inversely associated with sunshine, and positively associated with minimum temperature and windspeed. Light physical activity was inversely associated with windspeed, and positively associated with minimum temperature, cloud cover and sunshine. Moderate-to-vigorous physical activity was inversely associated with minimum temperature, rainfall, and windspeed, and positively associated with sunshine. For maximum temperature associations, an inverted-U curvilinear relationship was observed with both light and moderate-to-vigorous physical activity, and an exponential decay relationship with sleep (i.e. decreasing slope as maximum temperature increases). The directions of the associations observed in this study were largely consistent with previous literature.

Sleep

Sleep duration decreased as minimum temperature increased with an estimated reduction of 12 min across the 30 oC temperature range experienced by participants. This magnitude of change is consistent with a large global study in which a 9 min reduction was observed over the same temperature range [16]. Additionally, comparable reductions in sleep were observed in studies using self-reported sleep measures [35]. Participants in this study were, on average, within recommended sleep durations of 7 to 9 h, [36] and the modelled range of sleep duration change would not have moved the average person outside these recommendations. However, it is important to consider that nightly sleep needs are person- and context-specific. Finally, the acute effect of accumulated sleep reduction over days or weeks of very high overnight temperatures are wide ranging, including reduced cognitive ability, increased stress responsivity, emotional distress and reduced well-being [37]. The ability to maintain favourable indoor temperatures is highly resource-dependent and the effect of high overnight temperatures is likely to be greater for poor and low-resourced populations [38].

Physical activity

Light physical activity increased with minimum temperature, cloud cover and sunshine, and decreased as wind speed increased. These results are similar to the limited strength evidence in Turrisi et al.'s [15] review. No evidence was found for associations with cloud cover and sunshine in that review.

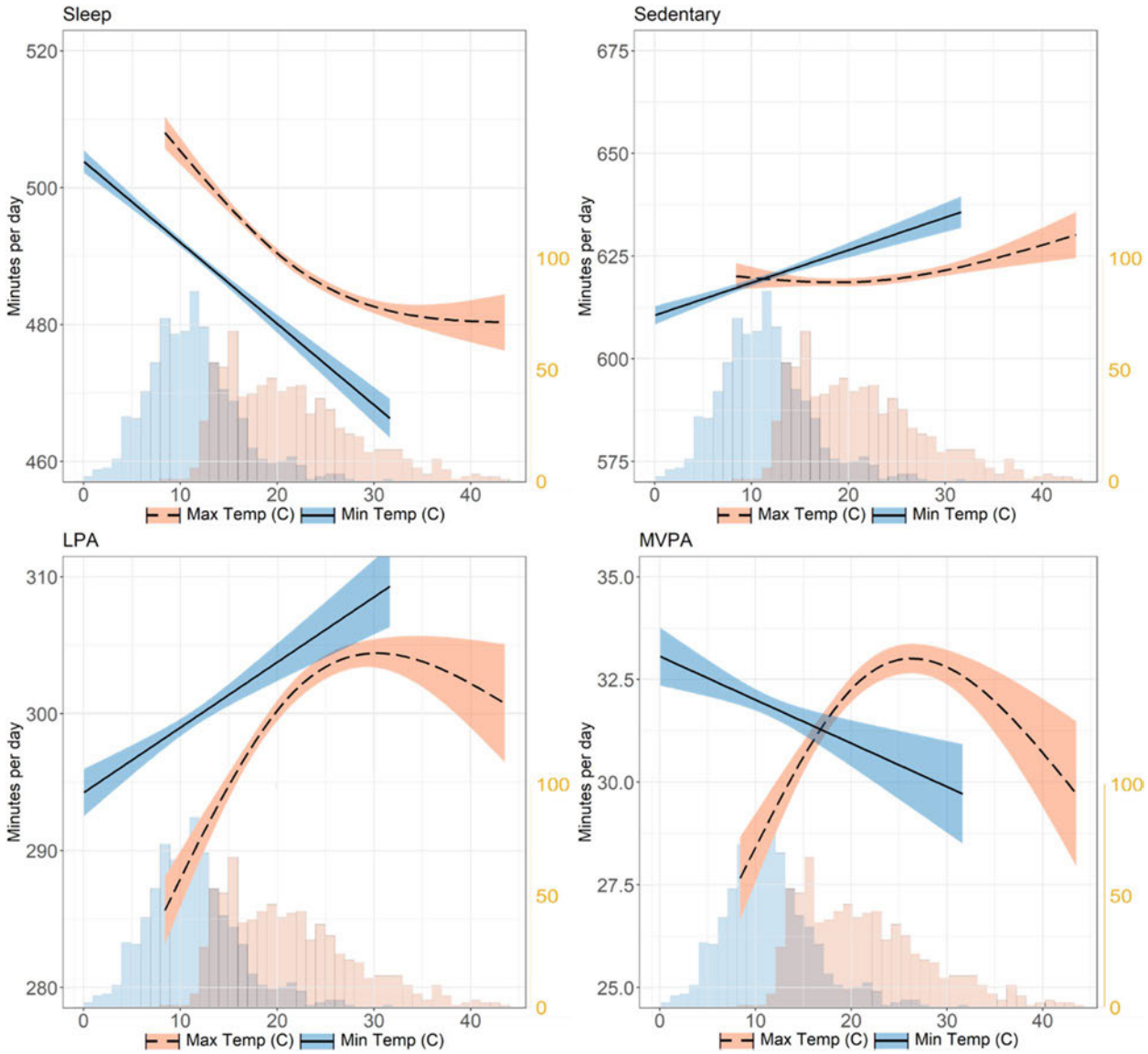


Fig. 1 Fitted line plot of daily maximum and minimum temperatures vs movement behaviours. Notes: Max Temp = maximum daily temperature (°C), Min Temp = minimum daily temperature (.°C). Coloured area represents 95% confidence intervals. Generalised additive models used to produce Max Temp smoothed line and generalised linear models used to produce Min Temp smoothed line. Right y-axis represents histogram showing frequency of temperature at 1 °C intervals for maximum daily temperature (blue) and minimum daily temperature (orange)

Moderate-to-vigorous physical activity decreased as minimum temperature, rain and wind increased, and increased as sunshine increased. Combining this with the curvilinear relationship of maximum temperature, it appears ideal conditions were dry, calm, sunny days where maximum temperatures ranged from 22 °C-32 °C. Turrisi et al [15]. reported similar results, with strong evidence for a curvilinear relationship with maximum temperature. Interestingly, the percentage of days where minimum recommended physical activity levels were achieved was relatively stable across the 20–40 oC maximum temperature range (51.9%-53.5% range across 5 oC groupings). However, there was a sharp decrease in the number of days when physical activity guidelines were met, when the maximum temperature was above 40 oC (44.9% vs 52.3% for days 35–40 oC). At the population level, this is a meaningful decline in moderate-to-vigorous physical activity on very hot days.

When considering the physical environment, extremes of weather have the potential to create unsafe environments for exercise, active transport and simply being

Table 4 Associations between movement behaviours and weather

	Units	Coefficient	[95% CI]	p
***Sleep** (model 1)*		*constant = 528 min/day*	*[520, 537]*	
Max temp	°C	**-2.31**	**[-2.88, -1.75]**	**<0.001**
Max temp^2	°C	**0.03**	**[0.02, 0.04]**	**<0.001**
Min temp	°C	**-0.37**	**[-0.59, -0.14]**	**0.001**
Rainfall	mm	0.04	[-0.11, 0.20]	0.564
Wind speed	km/h	0.47	[-0.04, 0.13]	0.264
Cloud cover	eighths	-0.26	[-0.62, 0.11]	0.168
Sunshine	min/day	-0.001	[-0.004, 0.003]	0.668
***Sedentary** (model 2)*		*constant = 610 min/day*	*[592, 628]*	
Max temp	°C	-0.03	[-0.74, 0.68]	0.932
Max temp^2	°C	0.01	[-0.01, 0.02]	0.263
Min temp	°C	**0.39**	**[0.11, 0.68]**	**0.006**
Rainfall	mm	0.14	[-0.05, 0.33]	0.139
Wind speed	km/h	**0.26**	**[0.16, 0.36]**	**<0.001**
Cloud cover	eighths	-0.35	[-0.80, 0.11]	0.137
Sunshine	min/day	**-0.02**	**[-0.03, -0.02]**	**<0.001**
***LPA** (model 3)*		*constant = 277 min/day*	*[263, 291]*	
Max temp	°C	**1.53**	**[1.02, 2.03]**	**<0.001**
Max temp^2	°C	**-0.03**	**[-0.04, -0.02]**	**<0.001**
Min temp	°C	**0.36**	**[0.16, 0.57]**	**0.002**
Rainfall	mm	-0.06	[-0.20, 0.07]	0.353
Wind speed	km/h	**-0.22**	**[-0.29, -0.15]**	**<0.001**
Cloud cover	eighths	**0.44**	**[0.11, 0.76]**	**0.008**
Sunshine	min/day	**0.02**	**[0.016, 0.024]**	**<0.001**
***MVPA** (model 4)*		*constant = 26 min/day*	*[22, 29]*	
Max temp	°C	**0.87**	**[0.64, 1.11]**	**<0.001**
Max temp^2	°C	**-0.01**	**[-0.02, -0.01]**	**<0.001**
Min temp	°C	**-0.41**	**[-0.51, -0.32]**	**<0.001**
Rainfall	mm	**-0.09**	**[-0.15, -0.03]**	**0.006**
Wind speed	km/h	**-0.10**	**[-0.13, -0.06]**	**<0.001**
Cloud cover	eighths	0.12	[-0.04, 0.27]	0.135
Sunshine	min/day	**0.003**	**[0.002, 0.005]**	**<0.001**

Results of multi-level mixed-effects linear regression analyses (one model per movement behaviour). Models adjusted for nesting of observations within participants, within families, within study waves. Bold and green shading indicates $p < 0.05$

LPA Light physical activity, *max temp* Maximum temperature, *max temp*^{2} Maximum temperature squared, *min temp* Minimum temperature, *MVPA* Moderate-to-vigorous physical activity

outdoors [12]. Rain reduces the quality of surfaces and visibility, wind reduces stability and increases surface debris, radiant heat can raise temperatures of asphalt, concrete and metal surfaces to unsafe levels [12]. It is easier to protect oneself from the elements with clothing and equipment (i.e. umbrella), or by staying indoors when being lightly active (i.e. walking), however this becomes more challenging with more demanding forms of activity such as cycling or running without access to indoor exercise equipment. Risk of injury also increases with more vigorous activities in less controlled environments.

Sedentary behaviour

The duration of sedentary behaviour increased as wind and minimum temperature increased, and decreased when sunshine increased. These findings are consistent with the moderate strength evidence reported by Turissi et al [15]. for temperature, and the limited strength evidence for windspeed [15]. No association between sedentary behaviour and rainfall or cloud cover is also consistent with Turissi et al.'s findings [15]. Interestingly, when looking at significant pairings of movement behaviours, seven involved sedentary behaviour and another movement behaviour, five of which were opposite association pairings. This suggests time allocation more commonly swaps between sedentary behaviour and the other movement behaviours. This swapping is supported by perceptions of extremes of weather as a barrier to physical activity, a negative correlate of sleep, and a positive correlate of sedentary behaviour [39–41].

Strengths and limitations

To our knowledge, this is the first longitudinal study of one year duration that captures 24-h movement behaviours in an adult population. The dataset included device-measured movement behaviour and climatic data. This is a large, high-quality dataset for answering the research questions at hand. There are a few limitations to consider. The sample size limited the study's power to explore potential participant sub-group differences. Data were collected in a single Australian city with a Mediterranean climate [29]. Thus, the findings are likely to be most applicable to other temperate climate regions (which includes parts of North and South America, Africa and Europe), and do not provide insight into extreme climates such as extremely cold or tropical climates. The population consisted of adults with primary-school-aged children, so adults' weather-related behaviour may additionally reflect the needs of children in their care. Furthermore, data collection took place from 2019–2021, much of which was within the Coronavirus disease 2019 (COVID-19) pandemic period. Due to Australia's strict quarantine approach, lifestyles of individuals residing in Adelaide were not harshly impacted by COVID-19, though there were periods in which working from home for non-essential workers was encouraged, and short periods of gym closures (less than one week durations, after an initial two-month shutdown).

Implications for intervention design

Several implications for intervention and health promotion campaigns should be considered. Firstly, the weather may influence intervention effects. For example, if an intervention spans months or seasons with meaningfully different weather conditions, weather should be considered when discussing findings, or potentially be included in statistical analyses. At the person-specific level, an interesting opportunity exists to explore a strategy known as just-in-time adaptive interventions. These are study designs that adapt the amount of intervention to the individual's context [42]. By leveraging longitudinal activity tracker data and combining this with weather forecasting, an opportunity exists to tailor health promotion messaging or intervention content to the individual at the specific time it is most needed. Future research in this area is warranted. Finally, community-level health promotion campaigns may be timed to target periods in the year, either by season or month, where less favourable weather conditions historically occur, i.e. promoting sleep and sleep hygiene in summer months, or ideas for "swapping" outdoor physical activity for indoor alternatives in winter and inclement weather.

Implications in the context of climate change

At present, we are amid an unprecedented climate crisis [43]. Global temperatures are increasing, rainfall patterns are changing, and the frequency of extreme weather events is on the rise [43]. This is having far-reaching negative health consequences [38, 44–46]. As these patterns progress, the number of days each year where weather conditions are favourable for movement behaviours and outdoor environments are accessible for recreation is likely to decrease.

There are several options for mitigating the negative health effects of a changing climate, at both the individual level and as a society. Individually, a push toward increasing active transport has health and financial benefits to the individual, whilst also reducing a person's CO_2 emissions and contribution to traffic congestion [47]. Whilst this is a viable option, a caveat is that this type of activity is highly weather dependent, and viability is likely to decrease as climate change progresses. Another approach is extremes of weather action planning. Provision of freely accessible sheltered and indoor recreation areas is needed, especially in more extreme climate locations and for low-resourced populations [48].

Conclusion

The results suggest modest significant associations between a range of weather variables and movement behaviours. In general, participants tended to be less active and more sedentary during extremes of weather and slept less as temperatures increased These findings have the potential to inform the timing and content of health promotion interventions at both the community and individual level, along with suggesting how health-related behaviours may be impacted over the coming decades by climate change.

Abbreviations

ARIA	Annual Rhythms In Adults' lifestyle and health study
COVID-19	Coronavirus disease 2019
LPA	Light physical activity
MVPA	Moderate-to-vigorous physical activity

Supplementary Information

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Additional file 1.

Additional file 2: Supplementary Table 1. Descriptive daily weather statistics.

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Authors' contributions

TF, CM, RC and FF were responsible for study inception and design. TF consolidated and cleaned data for analysis. All authors contributed to the statistical analysis plan with TF conducting the analyses. TF led manuscript writing and all authors conducted a critical revision and provided substantive feedback on the manuscript, in addition to approval of the final version.

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Availability of data and materials

Data used in the current study are available and may be obtained from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Ethics approval was provided by the University of South Australia Human Research Ethics committee (UniSA HREC, Protocol number: 201901) and participants provided written, informed consent prior to commencing participation.

Consent for publication

Not applicable.

Competing interests

The authors report no conflict of interest.

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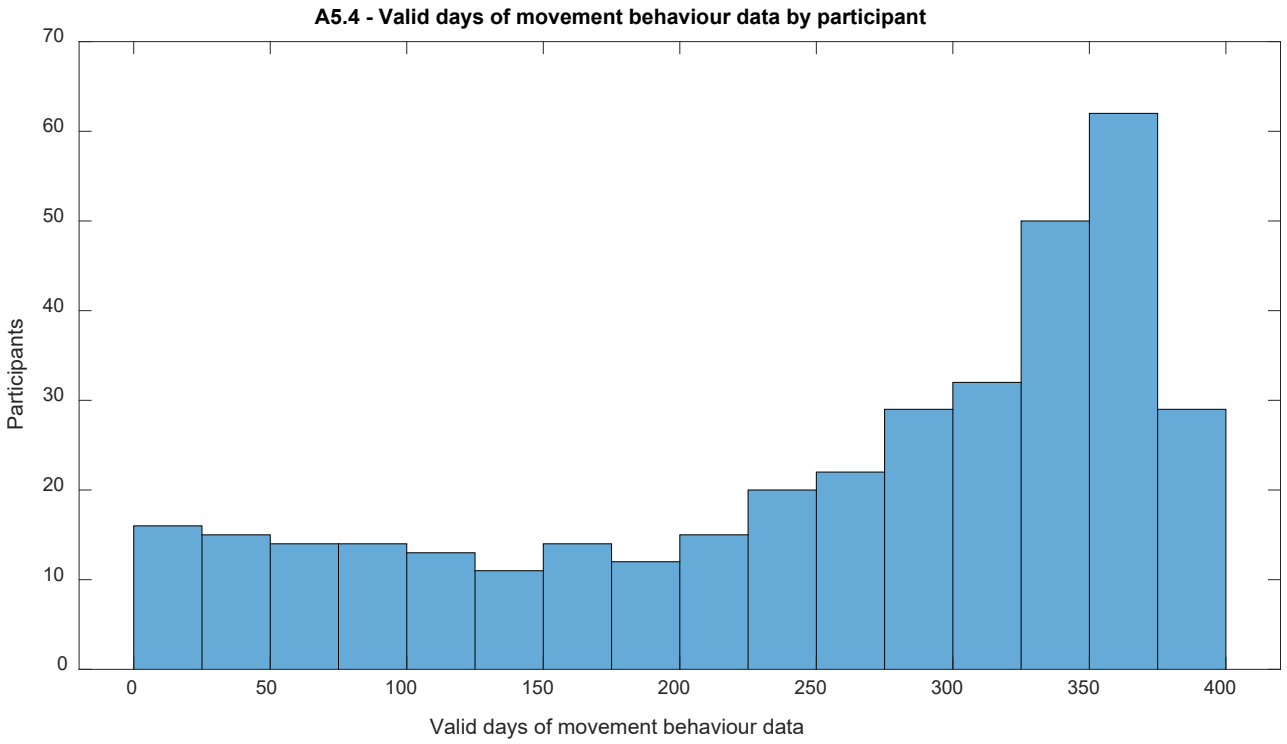
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Appendix A5.2 – Table of descriptive daily weather statistics

	Mean	SD	Min	Median	Max	IQR	Range
Min temperature (°C)							
Overall	11.3	4.5	0.4	11.0	31.6	5.4	31.2
Wave 1	11.4	4.9	0.04	20.5	31.6	5.9	31.6
Wave 2	11.2	4.1	1.78	11.0	26.4	4.9	24.6
Max temperature (°C)							
Overall	21.3	6.6	8.4	20.4	43.5	9.5	35.1
Wave 1	21.6	6.9	9.5	11.2	43.5	9.9	34.0
Wave 2	21.2	6.1	8.4	20.6	41.7	9.6	33.3
Rainfall (mm)							
Overall	1.5	3.8	0	0.04	33.2	0.8	33.2
Wave 1	1.4	3.9	0	0.04	32.2	0.7	32.2
Wave 2	1.4	3.7	0	0.04	33.2	1.0	33.2
Wind speed (km/h)							
Overall	23.1	6.8	9.3	22.3	46.0	8.9	36.7
Wave 1	23.2	7.0	9.3	22.7	43.2	9.8	33.9
Wave 2	23.2	6.8	10.8	22.1	45.7	8.2	34.9
Sunshine (h)							
Overall	7.8	3.9	0	8.5	13.9	6.1	13.9
Wave 1	7.7	3.9	0	8.35	13.8	6.3	13.8
Wave 2	8.1	3.8	0	8.6	13.9	5.8	13.9
Cloud cover (/8)							
Overall	4.4	2.4	0	4.8	8.0	4.3	8.0
Wave 1	4.5	2.5	0	4.8	8.0	4.3	8.0
Wave 2	4.3	2.3	0	4.5	8.0	4.0	8.0

Notes: Overall = 1/12/2019 to 31/12/2021, Wave 1 = 1/12/2019 to 31/12/2020, Wave 2 = 1/12/2020 to 31/12/2021. IQR = interquartile range, max = maximum, min = minimum, SD = standard deviation.


A5.4 - Valid days of movement behaviour data by participant
Participants
Valid days of movement behaviour data
0
10
20
30
40
50
60
70
0
50
100
150
200
250
300
350
400

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How do 24-h movement behaviours change during and after vacation? A cohort study

Ty Ferguson[1*], Rachel Curtis[1], Francois Fraysse[1], Timothy Olds[1], Dorothea Dumuid[1], Wendy Brown[2], Adrian Esterman[1] and Carol Maher[1]

Abstract

Background For adults, vacations represent a break from daily responsibilities of work – offering the opportunity to re-distribute time between sleep, sedentary behaviour, light physical activity (LPA) and moderate-to-vigorous physical activity (MVPA) across the 24-h day. To date, there has been minimal research into how activity behaviour patterns change on vacation, and whether any changes linger after the vacation. This study examined how daily movement behaviours change from before, to during and after vacations, and whether these varied based on the type of vacation and vacation duration.

Methods Data collected during the Annual Rhythms In Adults' lifestyle and health (ARIA) study were used. 308 adults (mean age 40.4 years, SD 5.6) wore Fitbit Charge 3 fitness trackers 24 h a day for 13 months. Minute-by-minute movement behaviour data were aggregated into daily totals. Multi-level mixed-effects linear regressions were used to compare movement behaviours during and post-vacation (4 weeks) to pre-vacation levels (14 days), and to examine the associations with vacation type and duration.

Results Participants took an average of 2.6 (SD = 1.7) vacations of 12 (SD = 14) days' (N = 9778 days) duration. The most common vacation type was outdoor recreation (35%) followed by family/social events (31%), rest (17%) and non-leisure (17%).

Daily sleep, LPA and MVPA all increased (+ 21 min [95% CI = 19,24] $p < 0.001$, + 3 min [95% CI = 0.4,5] $p < 0.02$, and + 5 min [95% CI = 3,6] $p < 0.001$ respectively) and sedentary behaviour decreased (-29 min [95% CI = -32,-25] $p < 0.001$) during vacation. Post-vacation, sleep remained elevated for two weeks; MVPA returned to pre-vacation levels; and LPA and sedentary behaviour over-corrected, with LPA significantly lower for 4 weeks, and sedentary behaviour significantly higher for one week. The largest changes were seen for "rest" and "outdoor" vacations. The magnitude of changes was smallest for short vacations (< 3 days).

Conclusions Vacations are associated with favourable changes in daily movement behaviours. These data provide preliminary evidence of the health benefits of vacations.

Trial registration The study was prospectively registered on the Australian New Zealand Clinical Trial Registry (Trial ID: ACTRN12619001430123).

Keywords Physical activity, Sedentary behaviour, Sleep, Vacation, Holiday, Movement behaviours, 24-h day, Time use

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Background

The demands of paid and unpaid work substantially reduce a person's ability to freely allocate their time. A standard workday accounts for approximately half an adult's waking hours [1, 2]. Additional time may need to be allocated to pre- and post-work related tasks (i.e. dressing, packing meals), along with commuting between home and the workplace. The average daily commute for workers globally is around an hour [3–5]. Further time allocation is needed for essential non-work tasks such as performing domestic duties, caring for loved ones, and attending appointments. Lastly, time must be given to self-care and sleep needs. After accounting for all these daily tasks, little is left to be allocated freely to such things as leisure pursuits, exercise, or rest.

When considering movement behaviours, throughout any day a person's activities may be considered on a movement continuum where they move between three broad behaviours of sleep, sedentary behaviour, and physical activity [6]. Further, a change in the time spent in one behaviour during a 24-h period necessitates an equal and opposite change across the remaining behaviours [7]. A person's occupation largely dictates what movement behaviour a person can engage in (e.g. desk-based occupations generally require long periods of sedentary time, while labour-intense occupations require long periods of physical activity). How a person commutes to employment also has an influence on movement behaviours; for example, passive transport (such as public transport) is typically sedentary, whereas active transport (i.e. walking or cycling) requires a degree of physical activity. Finally, the volume and timing of work and essential non-work tasks primarily restrict the window available for sleep, and limits the opportunity for leisure-time sedentary behaviour and physical activity.

Vacations are an extended and relatively uninterrupted break from the usual demands on a person's time, offering greater freedom in time allocation. Across a calendar year, a person is likely to take several vacations for multiple different purposes [8]. The purpose of vacations varies widely and is specific to the needs of the individual, their income and household demographics [8]. A vacation may occur at home or away, be primarily for leisure (e.g. attending events, visiting attractions), social (visiting family or friends), or active (e.g. hiking, bushwalking) pursuits, for rest and relaxation, or for non-leisure tasks (i.e. caring for others, home renovations).

Health-focused vacation research has largely been directed towards physical and mental health and well-being changes associated with taking vacations. Broadly, vacations are associated with positive changes in self-reported health and well-being [9–11]. Conversely, vacations are also associated with less desirable changes such as overconsumption of food [12]. Less is known about the associations between vacations and movement behaviours. It is generally understood that too little or too much sleep, too little physical activity, and too much sedentary behaviour are associated with poorer health, increased risk of chronic illness, and increased mortality [13–16]. Understanding the association between vacations and movement behaviours offers potential for targeted and timely interventions to improve or maintain favourable levels of each behaviour.

To our knowledge, just two studies have explored adults' movement behaviours during vacations. De Bloom et al. [17] recruited paid workers in The Netherlands ($n=54$) who went on vacations of longer than two weeks. Participants self-reported 7.4 h of sleep during vacation compared to 6.7 h pre-vacation. Cooper et al. [18] explored self-reported physical activity and sedentary behaviour levels before, during and after vacation in US adults ($n=122$). They found a non-significant trend towards an increase in total physical activity during vacation compared to pre-vacation and a significant decrease 6-weeks post-vacation compared to during vacation. Moderate physical activity was significantly lower on vacation compared to pre- and post-vacation whilst vigorous physical activity did not change across time points [18]. In this same study, additional unpublished data were obtained from the authors which showed a non-significant trend towards less sedentary behaviour during vacation compared to pre- and post-vacation [18, 19].

At present, no studies have used objective measures to explore changes in movement behaviours across the 24-h day during vacations. This study aims to address this gap by:

- Describing the characteristics of vacations across a 13-month period (number, duration, timing, key activities)
- Examining how objectively measured daily movement behaviours change from before, to during, and post-vacation periods, and how these vary depending on the type of vacation and vacation duration.
- Identifying the sociodemographic and occupation characteristics associated with favourable changes in movement behaviours during and after vacations.

Methods

Study design

This study used data from the *Annual Rhythms In Adults' lifestyle and health* (ARIA) prospective cohort study which collected daily 24-h movement behaviours in a cohort of Australian adults over a 13-month period. Full

details of the study protocol have been previously published [20].

Setting and procedure

ARIA included a community-based convenience sample of 375 adults, aged 18 to 65 years, recruited from the greater metropolitan area of Adelaide, South Australia.

Participants attended a face-to-face home visit, at which baseline measures (height, weight, and a demographic, health, and lifestyle characteristics survey) were collected and participants were provided with a Fitbit Charge 3 fitness tracker and Fitbit Aria body weight scale (Aria 2 or Aria Air scale; Fitbit Inc., San Francisco, CA, USA). Enrolment in the study occurred in two waves, with wave 1 data collection commencing on 1st Dec 2019 and concluding on 31st Dec 2020, and wave 2 data collection commencing on 1st Dec 2020 and concluding on 31st Dec 2021.

During the study, participants used the Fitbit devices daily and completed eight follow-up surveys which were spread throughout the 13-months, specifically December of the first calendar year, then January, March, April, June, August, October, and December of the second calendar year. These surveys comprised items relating to recreational physical activity, dietary intake, psychological wellbeing, weight perception/management, and work/holiday status. No further face-to-face sessions were needed unless for technical support. Upon completion of the study, participants received an honorarium of $100 and could keep their Fitbit Charge 3 and body weight scale if they wished.

Participants

Participants were recruited in two ways; either, they were parents of children enrolled in a separate cohort study, call Life on Holidays [21], or they were adults recruited from the general public who had primary (i.e. elementary) school-aged children. Participants from the general public were recruited via advertising in digital media (i.e. Facebook posts and paid advertisements) and print media.

Inclusion criteria were being 18 to 65 years old, being a parent/guardian of a child enrolled in Life on Holidays study or a parent/guardian of a child aged 5 to 12 years, residing in greater metropolitan Adelaide, having access to a Bluetooth-enabled mobile device or computer and home internet, able to understand English, and being ambulant. Exclusion criteria were pregnancy, having an implanted electronic medical device, or experiencing or receiving treatment for any life-threatening condition which impacted daily lifestyle and health.

Variables

Movement behaviours

Objectively measured physical activity, sedentary behaviour and sleep were collected using a wrist-worn Fitbit Charge 3 activity tracker (Fitbit Inc., San Francisco, USA). Participants wore the device on their non-dominant wrist, 24 h a day (except during showering, water-based activities or whilst charging the device) and were asked to sync data to their Fitbit user account at least every 5 days. Data were collected remotely via Fitnesslink software (Portal Australia, Adelaide, Australia), purpose-built for the ARIA study. Minute-by-minute activity data were recorded as sleep, sedentary behaviour, light physical activity, moderate physical activity, vigorous physical activity or non-wear according to Fitbit's proprietary algorithm. Previous models of Fitbit devices have demonstrated acceptable validity for moderate-to-vigorous physical activity (Flex compared to Actigraph GT3X + $r = 0.73$ [22]), sleep (compared to polysomnography: Charge 2 sensitivity = 0.96, specificity = 0.61; [23] Flex $r = 0.97$ [24]), sedentary time (compared to activPAL: ICC = 0.94, 95% CI: 0.92–0.96 [25]) and total daily energy expenditure (compared to doubly labelled water in free-living conditions: Flex $r_s = 0.84$ [26]).

Vacation

As part of each follow-up survey, participants reported any dates they had been on vacation since the last survey, if they went away from home on any of those vacation dates. Participants were asked to describe the main purpose of the vacation in an open-ended item. Main purpose responses were grouped into four categories: 1) *Family or social events* (e.g. visiting family, friends, attractions, or attending entertainment events, observing religious or cultural periods (e.g. Christmas, Easter), 2) *Rest and relaxation,* 3) *Outdoor recreation* (e.g. hiking, sports, fishing, boating, camping) or 4) *Non-leisure* (e.g. caring for others, household jobs, medical leave).

Employment status

At baseline, participants reported their occupation, whether they worked shift work, and whether they regularly worked on weekends. During each follow-up survey, participants reported their average hours of worked per week, categorised as either no hours, < 15 h, 15–35 h, or ≥ 36 h.

Demographics

At baseline, participants' demographic and health data were collected, including sex, date of birth, marital status, number of children in household, highest education level (below year 10, year 11, year 12 or equivalent,

certificate III/IV, advanced diploma/diploma, bachelor's degree, postgraduate or higher degree), combined gross household income (AUD < $50,000; $50,000-$99,999; $100,000-$199,999; ≥ $200,000) and presence of chronic conditions.

Baseline anthropometry

At the baseline home visit, a research assistant measured height (Leicester Height Measure MKII, Invicta Plastics Ltd, Leicester, England) and weight (Fitbit Aria smart scales, Fitbit Inc., San Francisco, USA).

Statistical analysis

Daily minute totals were calculated for sleep, sedentary behaviour, light physical activity and moderate-to-vigorous physical activity. For a day to be valid, a total of at least 18 h of data and a sleep period was required. Participants were included if they reported at least one vacation and had valid days of movement behaviour data pre-, during, and post-vacation.

For each vacation, mean daily sleep, sedentary, light physical activity, and moderate-to-vigorous physical activity time was calculated for the pre-vacation, during vacation, and post-vacation periods. Pre-vacation was defined as the fourteen days immediately prior to the vacation, excluding any vacation days from a previous vacation. Post-vacation was defined as the 28 days immediately after the vacation, considered in seven-day blocks (i.e. first, second, third and fourth week post-vacation), excluding any vacation days from a subsequent vacation.

All vacation and post-vacation periods were compared to pre-vacation periods for each movement behaviour using multi-level mixed-effects linear regression analyses. Analyses were completed in Stata 17 (StataCorp, College Station, TX, USA) with statistical significance set at 0.05. Random intercepts were used to account for the nested structure of the data (i.e. repeated measures within individuals, individuals within families, and families within waves). Movement behaviours were the dependent variables and were analysed in separate models. The vacation period (i.e. pre-, during or post vacation) was included as a fixed effect. The regression coefficients for vacation were used to identify the difference in daily minutes of movement behaviours during and post-vacation as relative to pre-vacation.

Additional sub-group analyses were completed for type of vacation (i.e., social, rest, outdoor recreation, non-leisure) and length of vacation (i.e., 3 days or less, 4–7 days, 8–14 days, over 14 days) using the same statistical approach as for overall vacation comparisons with each sub-group category analysed in separate models.

Interaction effects of participants' sociodemographic and occupation characteristics on movement behaviours during vacation were tested using multi-level mixed-effects linear regression (one model per movement behaviour, all sociodemographic and occupational characteristics included in each model). For these models only, Bonferroni corrections (p-value multiplied by total variables in the individual model) were used to adjust for the volume of comparisons.

Results

Participants

Of the 375 participants recruited, 308 went on at least one vacation where movement behaviour data were available. Participants were predominantly middle-aged (mean age 40.4 years, SD 5.6), overweight or obese, cohabitated, had 2–3 children at home, and were well-educated. Participants who reported paid employment were mostly day-workers (i.e. no shifts or weekends) and performed at least 15 h of work per week (see Table 1). This sample was similar to middle-aged Australian adults in terms of BMI (69% overweight or obese vs 66% of 35- to 44-year-old Australian adults [27]), sex (55.2% women vs 50.8% of 35- to 44-year-old Australian adults [28]) and smoking status (8.4% vs 11.7% of 35- to 44-year-old Australian adults [29]). However, there were slightly more people born in Australia (78.2% vs 67% of 30- to 49-year-old Australian adults [30]), in a domestic relationship (87.7% married or defacto vs 74% of 34- to 44-year-old Australian adults [30]), parents (100% were parents whereas 77% of Australian women aged 30 to 49 years report having children [30]), and employed persons (88.4% reported working vs 75% of 35- to 45-year-old Australian adults [30]). The sample had slightly higher rates of non-school education (83.4% with a non-school qualification vs approximately 75% of 30- to 50-year-old Australian adults [31]).

The characteristics of vacations

A total of 806 vacations were reported. Participants, on average, took less than three vacations per year (mean = 2.6, SD = 1.7) for a duration of 12 days on each occasion (mean = 12.1 days, SD = 14.1 days). The most common vacation purpose reported was *outdoor recreation* (35.2%), followed by *family or social events* (30.6%), *rest and relaxation* (17.1%) and *non-leisure activities* (16.6%). The distribution of vacations across the study period is shown in Fig. 1, showing that participants tended to take vacations more frequently during the Christmas and New Year period (> 50% of participants per day), school holidays, and on public holidays. Activity tracker non-wear time was consistent across the vacation period, with daily averages of 3.8% for pre-vacation, 3.9% during vacation and 3.7% post vacation. Compared to pre-vacation weekdays and weekends, movement behaviours during vacation appear closer to weekend patterns

Table 1 Participant and vacation characteristics ($n = 308$)

	N	(%)	Mean	(SD)
Participant characteristics				
Age			40.4	(5.6)
Weight (kg)			83.7	(21.2)
Height (cm)			170.6	(9.6)
Female	170	(55.2)		
Male	138	(44.8)		
Body Mass Index (kg/m^2)				
Underweight	1	(0.3)		
Normal	94	(30.5)		
Overweight	104	(33.8)		
Obese	109	(35.4)		
Smoker	26	(8.4)		
Born in Australia	241	(78.2)		
Aboriginal and Torres Strait Islander peoples	2	(0.6)		
Marital status				
Never married	15	(4.9)		
Married/de facto	270	(87.7)		
Separated, divorced or widowed	23	(7.5)		
Chronic illness				
None	140	(45.5)		
Single	88	(28.6)		
Multiple	80	(26.0)		
Adults in household				
One	28	(9.1)		
Two	264	(85.7)		
Three	12	(3.9)		
Four or more	4	(1.3)		
Children in household				
One	27	(8.8)		
Two	171	(55.5)		
Three	79	(25.7)		
Four or more	31	(10.1)		
Education				
Year 10 or less	15	(4.9)		
Year 11—12	36	(11.7)		
Certificate/Diploma	107	(34.7)		
University degree	150	(48.7)		
Occupation				
Managerial and professional	135	(43.8)		
Technical and clerical	70	(22.7)		
Community, personal service and sales	56	(18.2)		
Machinery operators, drivers, and labourers	12	(3.9)		
No job/other	35	(11.4)		
Income (Australian dollars)				
< $50,000	22	(7.1)		
Between $50,000 and $99,999	93	(30.2)		
Between $100,000 and $199,999	151	(49.0)		
≥ $200,000	42	(13.6)		
Hours worked per week				
None	31	(10.1)		
< 15	20	(6.5)		
15–35	107	(34.7)		
36 +	150	(48.7)		
Typical work pattern				
Weekdays only, no shift	214	(69.5)		
Weekdays and weekends	35	(11.4)		
Weekdays and shifts (inc. nights)	6	(1.9)		
Weekdays, weekends and shifts (inc. nights)	33	(10.7)		
Not applicable	20	(6.5)		
Vacation characteristics				
Total vacations	806			
Total vacation days	9778			
Vacations per participant			2.6	1.7
Vacation duration (days)			12.1	14.1
Vacation type (days)				
Outdoor recreation	2140	35.2		
Family or social events	3140	30.6		
Rest and relaxation	1618	17.1		
Non-leisure activities	2892	16.6		

than weekday (Supplementary Fig. 1). Vacation days closely resembled weekend days, with mean differences between vacations and non-vacation weekends ranging from −3.0% for sedentary behaviour to + 2.7% for sleep. By contrast, mean differences between non-vacation weekdays and vacations were very wide, ranging from −14.8% for MVPA to + 8.1% for sedentary behaviour.

Changes in movement behaviours across the vacation period

The average daily minutes spent in sleep, sedentary behaviour, and light, moderate and vigorous physical activity, over the vacation period are shown in Fig. 2.

Sleep increased significantly during vacation compared with pre-vacation (+ 21 min/day [95% CI = + 19, + 24], p < 0.001, + 4.4% change relative to pre-vacation). This significant increase persisted into the first and second weeks post-vacation (+ 8 min/day [95% CI = + 4, + 11], $p < 0.001$, + 1.5% and + 7 min/day [95% CI = + 4, + 10], $p < 0.001$, + 1.5% respectively) before returning to near-baseline levels.

Sedentary behaviour decreased significantly during vacation compared with pre-vacation (-29 min/day [95% CI = -32, -25], $p < 0.001$, -4.6%). In contrast, post-vacation sedentary behaviour increased significantly from

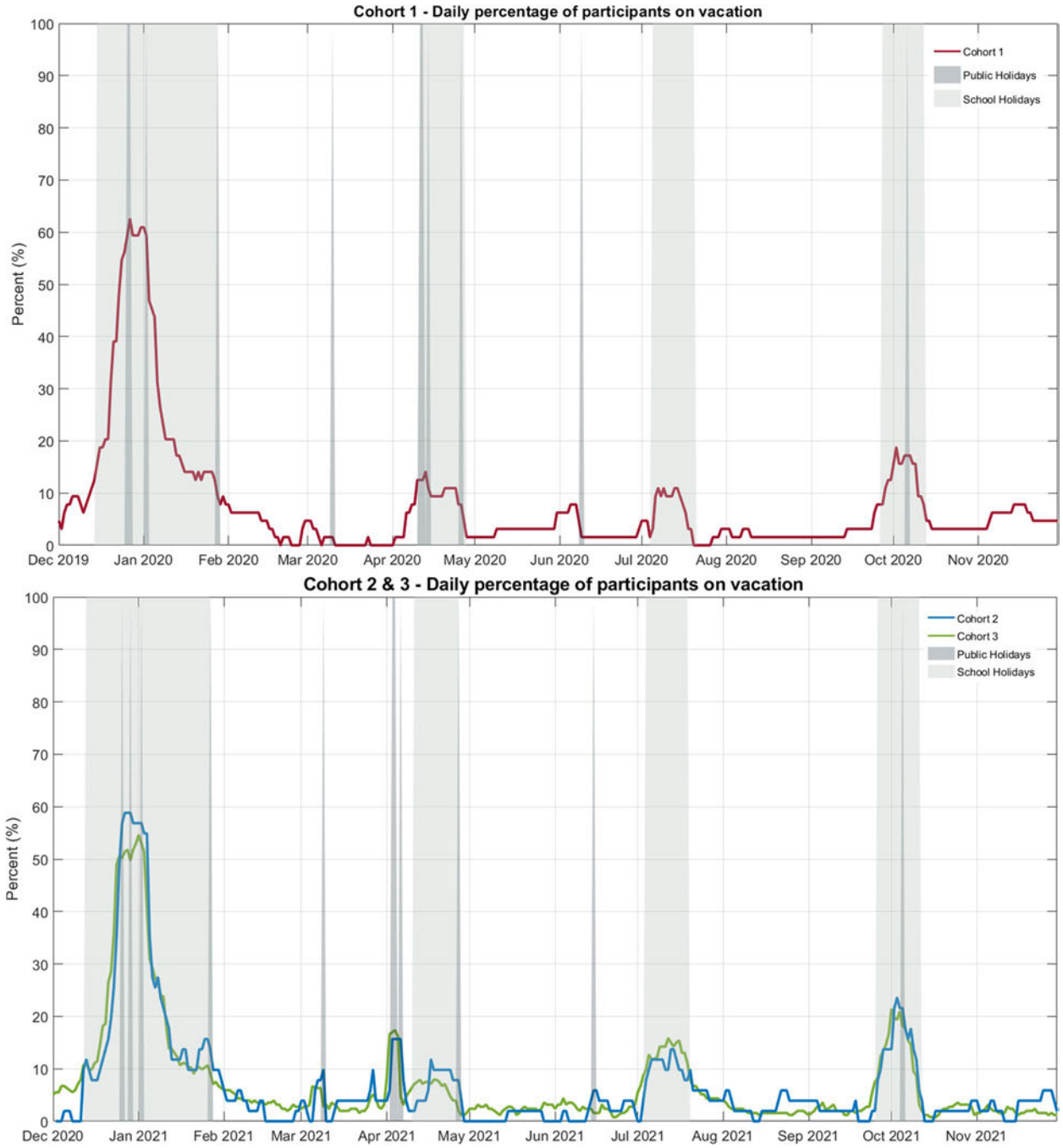


Fig. 1 Daily percentage of participants on vacation

pre-vacation levels (+5 min/day [95% CI = +1, +9], $p = 0.022$, +0.7%).

During and post-vacation time points were all significantly different to pre-vacation levels of light physical activity, however the direction differed. Light physical activity increased during vacation (+3 min/day [95% CI = 0, +5], $p = 0.021$, +0.9%) before decreasing relative to pre-vacation levels and persisting across each post-vacation timepoint (first week = -10 min/day [95% CI = -13,-8] $p < 0.001$, -3.4%; second week = -7 min/day [95% CI = -10, -5] $p < 0.001$, -2.4%; third week = -5 min/day [95% CI = -8, -2] $p = 0.001$, -1.6%; fourth week = -5 min/day [95% CI = -8, -2] $p < 0.001$, -1.7%).

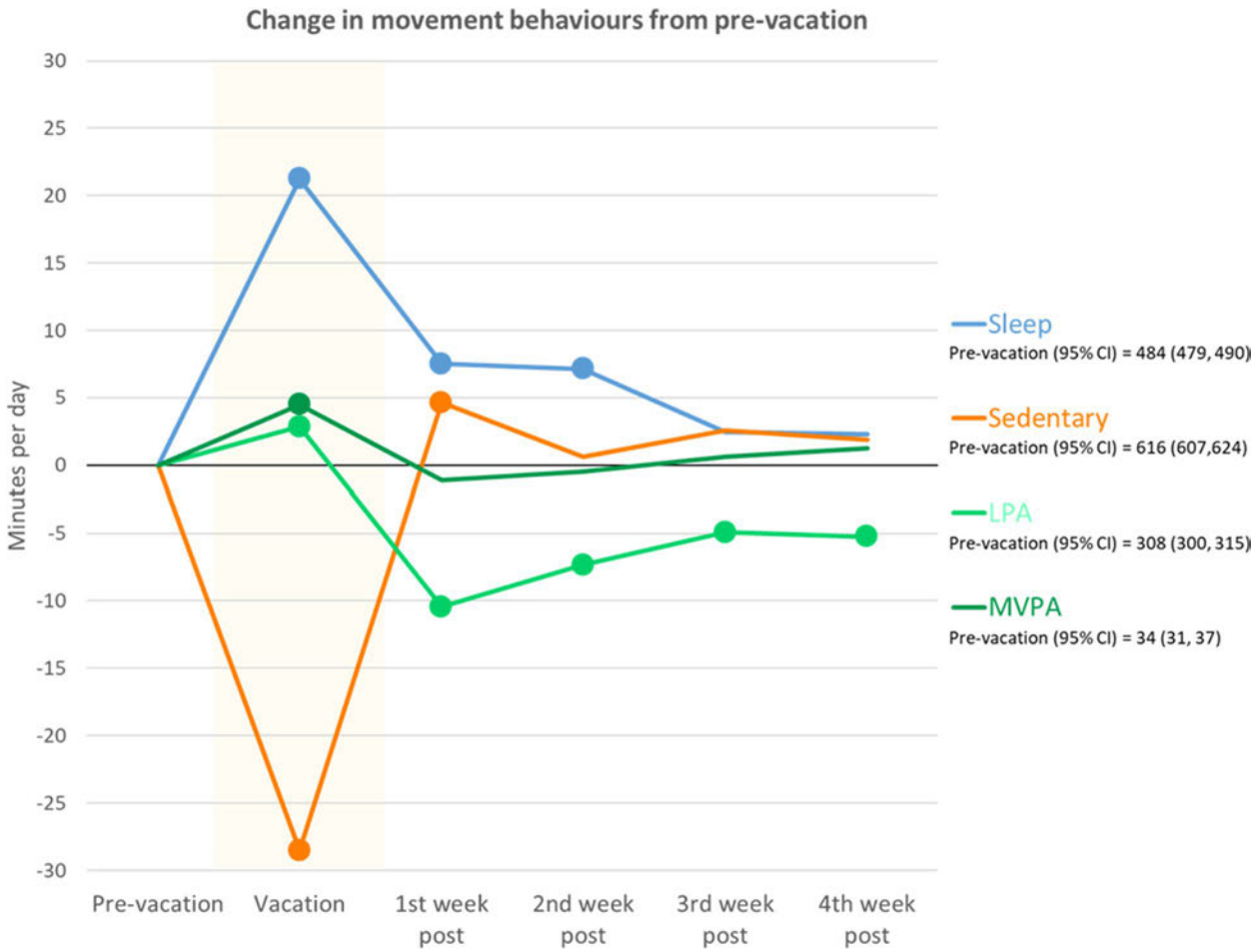


Fig. 2 Change in movement behaviours from pre-vacation. Figure notes: • = significant change from pre-vacation ($p < 0.05$). Pre-vacation is calculated as the mean of the 14 days immediately prior to any vacation. Vacation includes any vacation reported (mean length = 12.1 days, standard deviation = 14.1 days). LPA = light physical activity, MVPA = moderate-to-vigorous physical activity. Values reported in Supplementary Table 1

A significant increase in moderate-to-vigorous physical activity occurred during vacation (+5 min/day [95% CI = +3, +6], p < 0.001, +13.2%) before returning to pre-vacation levels immediately afterwards.

Vacation characteristics associated with changes in movement behaviours

Main vacation purpose

Movement behaviours across the vacation period according to main purpose of the vacation (i.e. family/social events, rest, outdoor recreation and non-leisure) were broadly similar to the overall vacation period patterns (Fig. 3 and Supplementary Table 1). Generally, increases in sleep, reductions in sedentary time, minimal changes in light physical activity, and small increases in moderate-to-vigorous physical activity were observed during vacation. Changes post-vacation appear to persist longer after outdoor recreation and family/social vacations than for rest and non-leisure vacations. Over-correction in the first week post-vacation occurred for sedentary behaviour after family/social vacations (decrease during, increase post) and light physical activity after outdoor vacations (increase during, decrease post).

Vacation length

Movement behaviour changes over the vacation period appeared to differed by vacation length (summarised in Fig. 4; full details of means, 95% confidence intervals, and *p* values are provided in Supplementary Table 1). Broadly, it appears the longer the vacation, the larger the change in sleep, and the smaller the change in sedentary behaviour, light and moderate-to-vigorous physical activity. Directions of change during vacation were largely consistent with overall patterns (sleep and physical activity increased, sedentary behaviour decreased, see Fig. 2), except for light physical activity during long vacations

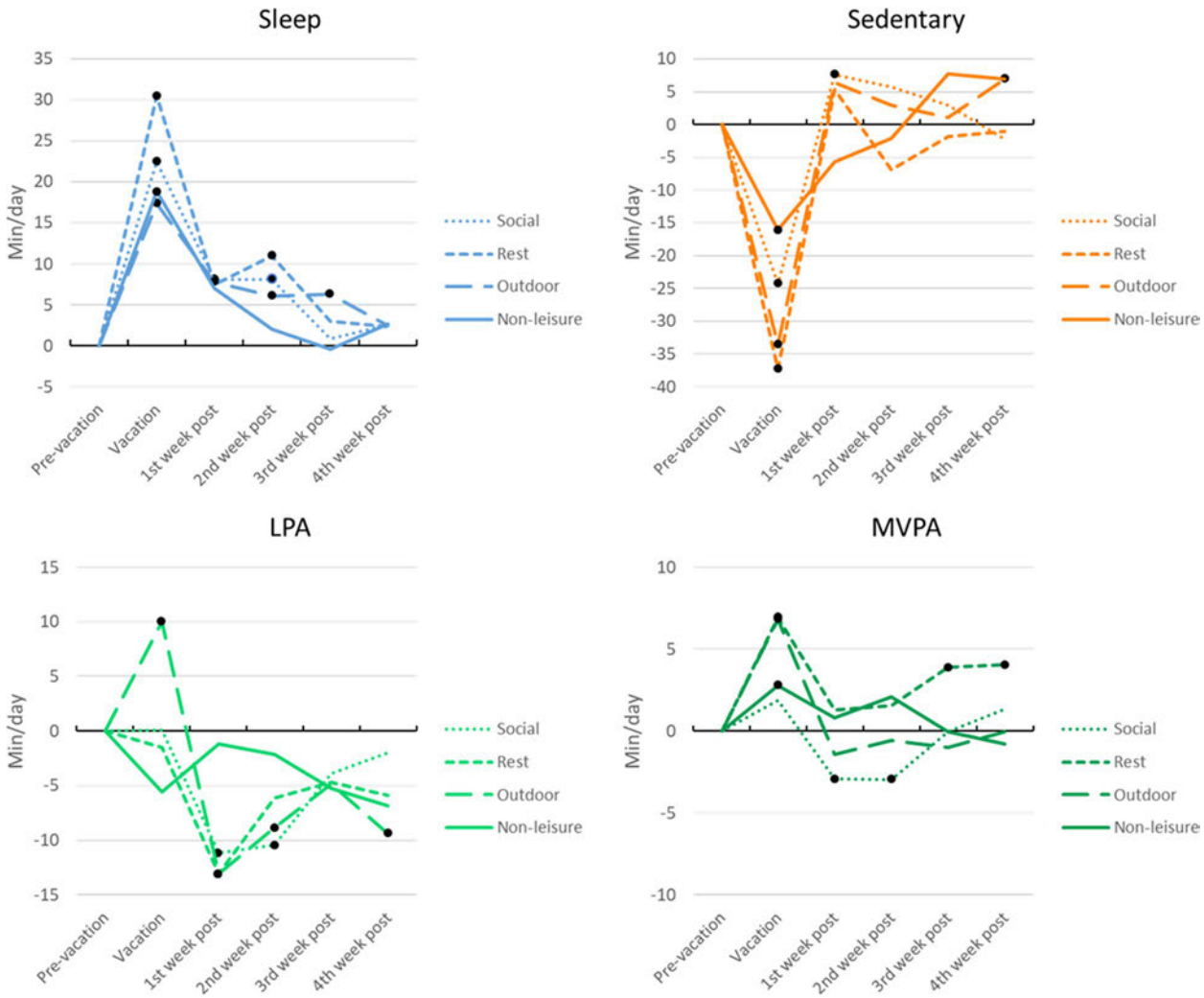


Fig. 3 Change in movement behaviours from pre-vacation by type of vacation. Figure note: • = significant change from pre-vacation ($p < 0.05$). LPA = light physical activity, MVPA = moderate-to-vigorous physical activity. Values reported in Supplementary Table 1. Social = Family or social events, e.g. visiting family, friends, attractions, or attending entertainment events, observing religious or cultural periods (Christmas, Easter), Rest = Rest and relaxation, Outdoor = Outdoor recreation, e.g. hiking, sports, fishing, boating, camping, Non-leisure = non-leisure tasks, e.g. caring for others, household jobs, medical leave

(> 2 weeks) where it decreased significantly by -9 min/day (95% CI = -12, -5, $p < 0.001$, -2.8%) from pre-vacation levels. In addition, the longevity of changes seems related to vacation length, with behaviours returning to pre-vacation levels almost immediately after short vacations, whereas changes persisted for several weeks after longer vacations for sleep and light physical activity.

Sociodemographic and occupation characteristics associated with changes in movement behaviours across the vacation period

Supplementary Table 2 contained results of interaction effects of participants' sociodemographic and occupation characteristics on movement behaviours during vacation. The changes in daily movement behaviours during vacation were unrelated to sociodemographic characteristics such as sex, age, education level, BMI, health status, occupational characteristics, and baseline activity levels. No comparisons were statistically significant post-Bonferroni corrections.

Discussion

Principal findings

Across all vacations, participants' movement behaviour patterns changed significantly in favourable directions (i.e., increased physical activity, decreased sedentary

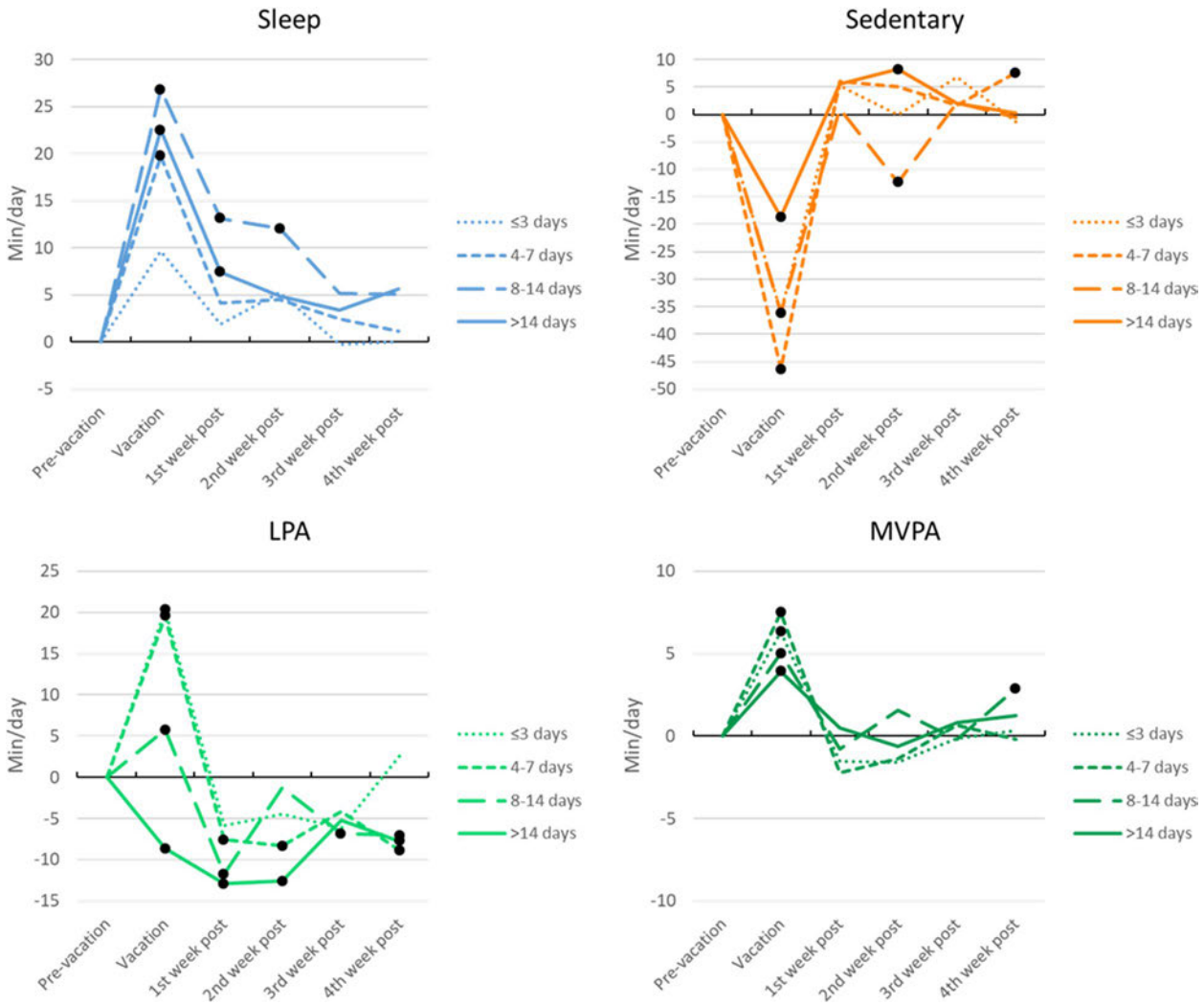


Fig. 4 Change in movement behaviours from pre-vacation by length of vacation. Figure note: • = significant change from pre-vacation ($p < 0.05$). LPA = light physical activity, MVPA = moderate-to-vigorous physical activity. Values reported in Supplementary Table 1

behaviour). The duration of vacation and type of vacation appeared to be associated movement behaviour changes, with vacations of 4 days to 1–2 weeks and outdoor recreation vacations associated with the most favourable changes. The largest significant during vacation changes were seen for vacations of > 1 week duration. Additionally, after vacations of > 1 week duration, sleep remained higher and light physical activity lower than pre-vacation for at least the first week. Finally, participant characteristics did not appear to influence changes in movement behaviours during or after vacation.

This study is the first to explore movement behaviours across the 24-h day using a longitudinal design with objective measures. Our findings were consistent with the two previous studies using self-reported measures. For example, de Bloom et al. [17] reported an increase in vacation sleep duration for vacations of longer than two-weeks. Of note, the change was almost twice as large as the current study (+42 min/day vs +23 min/day), which may be due to the method of measuring sleep. Furthermore, our findings for increased physical activity and decreased sedentary behaviour during vacation were broadly consistent with those reported by Cooper et al. [18], who reported non-significant trends, rather than significant findings as found in the current study. This may be due to the sample size, since the Cooper study involved 122 participants, which was less than half the sample size in our study.

The most consistent favourable changes across movement behaviours occurred in the 4 days to 2-week range, with these changes appearing to persist longer, the longer the vacation. This is consistent with the law

of inertia, where people have set patterns of time use which are difficult to perturb [32]. When a perturbation does occur, the tendency is for behaviour to snap back to initial patterns once the short-term disruption (i.e. a vacation) is removed [32]. The longer the disruption, the greater the change, and the slower the return to pre-existing levels [32].

When considering the type of vacation, outdoor recreation was the only category where all movement behaviours had significant favourable changes during vacation. This may be because outdoor recreation vacations are ideally suited to physical activity with two important facilitators, the natural environment and free time, available in abundance [33]. Further, increased physical activity has been shown to have a positive effect on sleep quality, particularly duration [34, 35].

Most participants in this study worked in office-based occupations, on a Monday-to-Friday schedule. The large decrease in sedentary behaviour from weekdays to weekends is consistent with previous literature of office workers [36] and is also observed in the change from pre-vacation to during vacation. The opposite change occurred for sleep and physical activity, with both increasing on weekends and during vacations, relative to weekdays and pre-vacation respectively. The overall consistent effect of weekends and vacations on movement behaviours is likely a product of people not needing to go to work, removing long hours of sedentary employment, and increasing time available to freely allocate across movement behaviours. This would suggest vacations are like very long weekends. When considering post-vacation, the over-correction in sedentary behaviour observed during the first week, where it was significantly increased, may be attributed to a workload catch-up, where tasks accumulated during vacation may need to be added to usual work demands [37].

Strengths and limitations

To our knowledge, this is largest ever study of movement behaviour patterns during vacations, as well as the first study of vacations that captures 24-h objective movement behaviour data. Use of a remote data collection method meant there were minimal barriers to participants' involvement in the study when away from home.

This study explored activity behaviour patterns exclusively, with minimal knowledge of participant motivations, vacation destinations, itineraries or vacation companions. This sample had a high concentration of vacations during the Australian summer (December and January) and it is possible the time of year when a vacation is taken may be associated with movement patterns, however, this was beyond the scope of the current study. The study sample was generally representative of middle-aged Australians. However, as the sampling frame was parents of primary school age children, when compared with national population data there were slight over-representation of people who were married / in de facto relationships, parents, employed persons and those with higher education. It must be acknowledged that the participants were all parents and city-dwellers residing in one major Australian city, and that the generalisability of the findings, especially for adults without children (approximately 23% of middle aged Australians) and those who reside in non-urban areas (14% of Australians) is unclear. The statistical analyses used in this study explored the 24-h day using individual models without direct comparison between movement behaviours. An alternative and more complex approach to account for direct interactions would be compositional data analysis. Whilst the sample size is adequately powered for overall analyses, it's possible sub-group analyses on participant characteristics may be underpowered. Finally, data collection occurred during the COVID-19 pandemic. Importantly, within state travel was minimally impacted in South Australia during the study period. However, interstate and international travel was largely restricted. Australia adopted an elimination approach to the virus with widespread and varied border closures along with strict quarantine rules, adding up to two additional weeks to any cross-border travel. Participant choices of vacation destination, duration and vacation activities are likely to have differed from pre-COVID travel.

Implications

Whilst the findings of this study suggest there may be an optimal length and type of vacation to yield the greatest favourable changes, the availability of vacation leave will ultimately dictate vacation options. Minimum yearly paid leave entitlements vary widely around the world. In Australia, the minimum is 4 weeks [38], whereas some European countries are higher (e.g. 6 weeks in France [38]). The US has no minimum paid leave requirements [39], though about three-quarters of US workers receive 2–3 weeks of paid leave [40]. Workers in countries with low allocations, such as the US, may prefer multiple short breaks, rather than a single 2-week block each year. Conversely, high allocation countries such as France, allow for multiple 2-week vacations per year, where potentially favourable changes may be repeated and spread across the year. Additionally, leave availability may influence vacation type as some options may not be feasible on short breaks where travel time to the destination is prohibitive.

Future directions

Changes observed during vacation are likely the result of a combination of factors, specific to each vacation. Whilst it is difficult to replicate this outside of the vacation setting, potential exists for interventions around the vacation. Future research should include experimental study designs, exploring interventions that encourage favourable behaviour change in the lead up to or after vacations. An interesting finding from the current study is the over-correcting of sedentary behaviour and light physical activity post-vacation toward less favourable directions which would suggest interventions aimed at reducing sedentary behaviour and increasing light physical activity at this timepoint may be warranted. There is potential to explore what specific behaviours a person engages with during vacation (i.e., increased walking, earlier bedtime) that likely produced favourable changes and aim to incorporate these habits into daily life post-vacation. Another important consideration is exploring potential changes in mental health and well-being during vacation and how they are associated with movement behaviours. Exploring sleep changes in chronic undersleepers would be of interest to observe if the same increases in sleep duration observed in this study are replicated in that population. Finally, a larger sample or a sample followed for a longer duration would allow more in-depth explorations into particular sub-groups identified within this study, i.e. vacation purpose, demographic subgroups.

Conclusion

During vacations, favourable changes in movement behaviours (i.e., more physical activity and less sedentary behaviour) were observed, with these changes most pronounced in vacations of 4 days to 2 weeks long, and during vacation for outdoor recreation. Post-vacation, moderate-to-vigorous physical activity quickly returned to pre-vacation levels whereas sedentary behaviour and light physical activity tended to over-correct. Increases in sleep were apparent for around two weeks post-vacation, particularly after vacations longer than one week, and after outdoor and social vacations. These data provide preliminary evidence of the health benefits of vacations. Findings suggest that interventions timed immediately post-vacation may help combat unfavourable over-corrections observed in sedentary behaviour and light physical activity.

Abbreviations

ARIA	Annual Rhythms In Adults' lifestyle and health study
BMI	Body mass index
LPA	Light physical activity
MVPA	Moderate-to-vigorous physical activity

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12966-023-01416-2.

Additional file 1: Supplementary Figure 1. Pre-vacation weekdays and weekends as a percent difference from vacation days.

Additional file 2: Supplementary Table 1. Coefficients, standard errors and *p* values of data presented in Figs. 2, 3 and 4.

Addtional file 3: Supplementary Table 2. During vacation changes in movement behaviours by participant characteristics.

Acknowledgements

Not applicable.

Authors' contributions

TF, CM, RC and FF were responsible for study inception and design. TF consolidated and cleaned data for analysis. All authors contributed to the statistical analysis plan with TF conducting the analyses. TF led manuscript writing and all authors conducted a critical revision and provided substantive feedback on the manuscript. The author(s) read and approved the final manuscript.

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Availability of data and materials

Data used in the current study are available and may be obtained from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Ethics approval was provided by the University of South Australia Human Research Ethics committee (UniSA HREC, Protocol number: 201901) and participants provided written, informed consent prior to commencing participation.

Consent for publication

Not applicable.

Competing interests

The authors report no conflict of interest.

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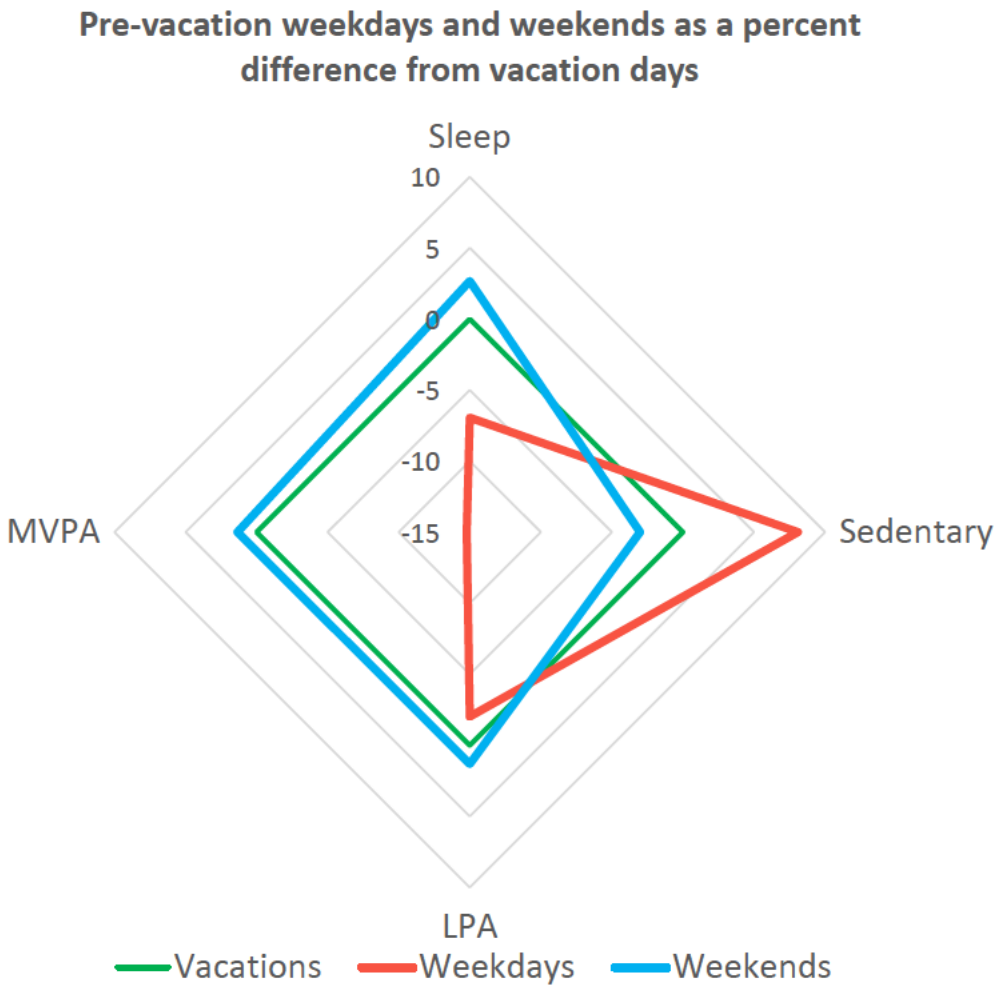
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Appendix A6.2 - Pre-vacation weekdays and weekends as a percent difference from vacation days

Notes: LPA = light physical activity, MPVA = moderate-to-vigorous physical activity.

Supplementary Table 1: coefficients, standard errors and p values of data presented in figures 1, 2 and 3.

			Change from pre-vacation											
		Pre-vacation	Vacation			1st week post			2nd week post			3rd week post			4th week post		
		cons [95% CI]	coeff	[95% CI]	p	coeff	[95% CI]	p	coeff	[95% CI]	p	coeff	[95% CI]	p	coeff	[95% CI]	p
Pre, during and post vacation activity profiles (Figure 1)																	
All vacations	Sleep	484.3 [478.7, 489.8]	**21.2**	**[18.6, 23.9]**	**<0.001**	**7.5**	**[4.4, 10.6]**	**<0.001**	**7.1**	**[4.0, 10.3]**	**<0.001**	2.5	[-0.7, 5.7]	0.131	2.3	[-1.0, 5.5]	0.172
	Sedentary	615.5 [606.9, 624.2]	**-28.5**	**[-31.9, -25.2]**	**<0.001**	**4.6**	**[0.7, 8.6]**	**0.022**	0.6	[-3.4, 4.7]	0.760	2.6	[-1.5, 6.6]	0.219	1.9	[-2.3, 6.0]	0.377
	LPA	307.6 [300.4, 314.9]	**2.8**	**[0.4, 5.3]**	**0.021**	**-10.4**	**[-13.3, -7.6]**	**<0.001**	**-7.3**	**[-10.2, -4.5]**	**<0.001**	**-4.9**	**[-7.8, -2.0]**	**0.001**	**-5.2**	**[-8.2, -2.3]**	**<0.001**
	MVPA	34.0 [31.3, 36.7]	**4.5**	**[3.4, 5.6]**	**<0.001**	-1.1	[-2.5, 0.2]	0.096	-0.5	[-1.9, 0.8]	0.465	0.6	[-0.7, 2.0]	0.370	1.3	[-0.1, 2.7]	0.072
Vacation activity profiles by type of vacation (Figure 2)																	
Social	Sleep	486.1 [477.3, 494.9]	**22.5**	**[17.9, 27.0]**	**<0.001**	**8.1**	**[2.9, 13.4]**	**0.002**	**8.1**	**[2.7, 13.5]**	**0.003**	0.8	[-4.6, 6.2]	0.769	2.5	[-2.9, 8.0]	0.360
	Sedentary	611.1 [598.0, 624.2]	**-24.3**	**[-30.1, -18.5]**	**<0.001**	**7.6**	**[0.9, 14.3]**	**0.025**	5.7	[-1.2, 12.6]	0.104	2.9	[-4.0, 9.8]	0.408	-2.2	[-9.2, 4.7]	0.532
	LPA	309.8 [299.0, 320.5]	0.1	[-4.0, 4.2]	0.953	**-11.2**	**[-15.9, -6.5]**	**<0.001**	**-10.5**	**[-15.3, -5.6]**	**<0.001**	-3.9	[-8.8, 1.0]	0.119	-2.0	[-6.9, 2.9]	0.423
	MVPA	34.2 [30.5, 37.9]	1.9	[-0.1, 3.8]	0.065	**-2.9**	**[-5.2, -0.7]**	**0.011**	**-3.0**	**[-5.3, -0.6]**	**0.013**	-0.1	[-2.4, 2.3]	0.953	1.3	[-1.0, 3.7]	0.265
Rest	Sleep	481.7 [471.8, 491.5]	**30.5**	**[23.9, 37.1]**	**<0.001**	7.4	[-0.1, 15.0]	0.055	**11.0**	**[3.4, 18.6]**	**0.005**	2.9	[-4.7, 10.6]	0.448	2.4	[-5.4, 10.2]	0.547
	Sedentary	627.4 [612.5, 642.2]	**-37.3**	**[-45.4, -29.3]**	**<0.001**	5.3	[-3.9, 14.6]	0.257	-6.9	[-16.3, 2.4]	0.146	-1.8	[-11.2, 7.5]	0.700	-1.1	[-10.6, 8.4]	0.821
	LPA	299.7 [286.7, 312.7]	-1.5	[-7.0, 4.1]	0.603	**-13.1**	**[-19.4, -6.7]**	**<0.001**	-6.2	[-12.6, 0.3]	0.060	-4.7	[-11.1, 1.7]	0.148	-5.9	[-12.4, 0.7]	0.080
	MVPA	33.3 [28.0, 38.6]	**6.9**	**[4.2, 9.6]**	**<0.001**	1.3	[-1.8, 4.4]	0.418	1.5	[-1.6, 4.7]	0.336	**3.9**	**[0.7, 7.0]**	**0.016**	**4.0**	**[0.8, 7.2]**	**0.014**
Outdoor	Sleep	480.7 [473.6, 487.7]	**17.4**	**[12.7, 22.0]**	**<0.001**	**7.8**	**[2.5, 13.0]**	**0.004**	**6.1**	**[0.9, 11.3]**	**0.023**	**6.3**	**[1.0, 11.7]**	**0.020**	2.5	[-2.9, 7.8]	0.370
	Sedentary	613.7 [601.2, 626.3]	**-33.6**	**[-39.6, -27.6]**	**<0.001**	6.4	[-0.4, 13.1]	0.065	2.9	[-3.8, 9.6]	0.395	1.0	[-5.8, 7.9]	0.770	**7.0**	**[0.1, 13.9]**	**0.048**
	LPA	310.9 [300.7, 321.1]	**10.0**	**[5.7, 14.3]**	**<0.001**	**-13.1**	**[-17.9, -8.2]**	**<0.001**	**-8.9**	**[-13.7, -4.0]**	**<0.001**	-4.8	[-9.8, 0.1]	0.057	**-9.4**	**[-14.4, -4.4]**	**<0.001**
	MVPA	36.5 [32.7, 40.3]	**6.8**	**[4.8, 8.8]**	**<0.001**	-1.4	[-3.7, 0.8]	0.216	-0.6	[-2.8, 1.7]	0.627	-1.0	[-3.3, 1.3]	0.392	-0.1	[-2.4, 2.3]	0.955
Non-leisure	Sleep	487.5 [476.8, 498.2]	**18.8**	**[12.3, 25.2]**	**<0.001**	7.1	[-0.7, 14.8]	0.074	2.0	[-5.8, 9.9]	0.614	-0.4	[-8.4, 7.6]	0.921	2.6	[-5.6, 10.9]	0.527
	Sedentary	607.3 [590.4, 624.2]	**-16.1**	**[-24.4, -7.9]**	**<0.001**	-5.7	[-15.6, 4.1]	0.253	-2.1	[-12.1, 7.9]	0.675	7.8	[-2.5, 18.0]	0.137	6.9	[-3.5, 17.4]	0.193
	LPA	313.9 [299.1, 328.7]	-5.5	[-11.5, 0.4]	0.068	-1.2	[-8.2, 5.9]	0.748	-2.1	[-9.3, 5.0]	0.559	-5.3	[-12.6, 2.1]	0.161	-6.8	[-14.4, 0.7]	0.075
	MVPA	32.9 [27.7, 38.1]	**2.8**	**[0.1, 5.5]**	**0.046**	0.8	[-2.4, 4.1]	0.620	2.1	[-1.2, 5.4]	0.214	-0.1	[-3.4, 3.3]	0.969	-0.8	[-4.2, 2.7]	0.658
Vacation activity profiles by length of vacation (Figure 3)																	
≤ 3 days	Sleep	481.5 [470.9, 492.1]	9.6	[-1.4, 20.7]	0.087	1.9	[-5.4, 9.2]	0.616	5.3	[-2.2, 12.8]	0.169	-0.3	[-7.9, 7.4]	0.945	0.1	[-7.9, 8.0]	0.988
	Sedentary	615.6 [598.8, 632.4]	**-36.0**	**[-50.3, -21.6]**	**<0.001**	5.2	[-4.3, 14.7]	0.287	-0.1	[-9.9, 9.7]	0.988	6.8	[-3.2, 16.7]	0.182	-1.3	[-11.6, 9.0]	0.806
	LPA	309.3 [294.9, 323.6]	**20.3**	**[10.8, 29.9]**	**<0.001**	-5.8	[-12.2, 0.5]	0.069	-4.4	[-10.9, 2.1]	0.180	-6.2	[-12.8, 0.4]	0.067	2.6	[-4.2, 9.5]	0.452
	MVPA	35.1 [30.1, 40.2]	**6.3**	**[1.7, 10.9]**	**0.007**	-1.5	[-4.5, 1.5]	0.326	-1.6	[-4.7, 1.5]	0.314	-0.2	[-3.3, 3.0]	0.921	0.3	[-2.9, 3.6]	0.840
4 to 7 days	Sleep	486.5 [479.3, 493.8]	**19.7**	**[13.9, 25.6]**	**<0.001**	4.1	[-0.9, 9.2]	0.109	4.5	[-0.6, 9.5]	0.082	2.5	[-2.7, 7.6]	0.347	1.1	[-4.0, 6.3]	0.668
	Sedentary	617.5 [604.7, 630.4]	**-46.3**	**[-54.2, -38.5]**	**<0.001**	6.0	[-0.9, 12.8]	0.087	5.0	[-1.8, 11.8]	0.153	1.6	[-5.3, 8.5]	0.641	**7.6**	**[0.6, 14.5]**	**0.033**
	LPA	304.3 [294.0, 314.6]	**19.6**	**[14.1, 25.1]**	**<0.001**	**-7.6**	**[-12.4, -2.8]**	**0.002**	**-8.3**	**[-13.1, -3.6]**	**0.001**	-4.2	[-9.0, 0.6]	0.089	**-8.9**	**[-13.7, -4.0]**	**<0.001**
	MVPA	33.9 [29.9, 37.9]	**7.5**	**[4.9, 10.1]**	**<0.001**	-2.2	[-4.5, 0.04]	0.054	-1.4	[-3.7, 0.9]	0.236	0.6	[-1.7, 3.0]	0.582	-0.2	[-2.5, 2.1]	0.861
8 to 14 days	Sleep	475.9 [467.6, 484.2]	**26.8**	**[21.1, 32.5]**	**<0.001**	**13.1**	**[6.5, 19.8]**	**<0.001**	**12.0**	**[5.5, 18.6]**	**<0.001**	5.2	[-1.5, 11.9]	0.128	5.1	[-1.7, 11.8]	0.141
	Sedentary	616.4 [603.0, 629.7]	**-36.1**	**[-43.3, -29.0]**	**<0.001**	1.0	[-7.2, 9.3]	0.805	**-12.4**	**[-20.6, -4.2]**	**0.003**	2.1	[-6.3, 10.4]	0.624	-0.5	[-8.9, 7.9]	0.910
	LPA	313.0 [301.4, 324.5]	**5.7**	**[0.7, 10.8]**	**0.027**	**-11.8**	**[-17.6, -5.9]**	**<0.001**	-1.3	[-7.1, 4.5]	0.661	**-6.8**	**[-12.7, -0.9]**	**0.024**	**-7.1**	**[-13.0, -1.1]**	**0.021**
	MVPA	36.4 [31.8, 41.0]	**5.0**	**[2.6, 7.4]**	**<0.001**	-0.8	[-3.6, 2.0]	0.575	1.5	[-1.2, 4.3]	0.276	-0.2	[-3.0, 2.6]	0.900	**2.9**	**[0.03, 5.7]**	**0.048**
> 14 days	Sleep	483.1 [475.2, 490.9]	**22.5**	**[18.4, 26.7]**	**<0.001**	**7.4**	**[1.8, 13.1]**	**0.010**	4.9	[-0.9, 10.7]	0.101	3.4	[-2.4, 9.2]	0.248	5.6	[-0.1, 11.4]	0.054

Sedentary	612.4 [600.4, 624.4]	**-18.7 [-23.8, -13.6]**	**<0.001**	5.5 [-1.5, 12.5]	0.122	**8.2 [1.1, 15.4]**	**0.024**	2.0 [-5.1, 9.1]	0.586	0.2 [-6.8, 7.3]	0.945
LPA	311.2 [301.4, 321.1]	**-8.6 [-12.4, -4.8]**	**<0.001**	**-12.9 [-18.1, -7.8]**	**<0.001**	**-12.6 [-17.8, -7.3]**	**<0.001**	-5.2 [-10.4, 0.1]	0.053	**-7.8 [-13.0, -2.5]**	**0.004**
MVPA	34.3 [30.7, 37.9]	**3.9 [2.2, 5.7]**	**<0.001**	0.5 [-1.8, 2.9]	0.671	-0.6 [-3.0, 1.8]	0.602	0.8 [-1.6, 3.2]	0.503	1.2 [-1.1, 3.6]	0.309

Notes: Bold values denotes significant change from pre-vacation ($p<0.05$). Coeff = coefficient, cons = constant, CI = confidence interval, LPA = light physical activity, MVPA = moderate-to-vigorous physical activity.

Appendix A6.4 – Table of during vacation changes in movement behaviours by participant characteristics.

		Sleep			Sedentary			LPA			MVPA		
		Coeff	[95% CI]	p	Coeff	[95% CI]	p	Coeff	[95% CI]	p	Coeff	[95% CI]	p
Vacation change (all characteristics = cons)		30.4	[-9.0, 69.7]	0.130	-41.8	[-104.2, 20.6]	0.189	12.5	[-38.4, 63.4]	0.630	3.1	[-13.8, 19.9]	0.721
Sex	cons = male												
	female	-4.2	[-16.1, 7.6]	0.482	11.9	[-7.2, 30.9]	0.222	-9.5	[-25.2, 6.1]	0.234	-3.0	[-8.0, 2.1]	0.251
Age		-0.1	[-0.9, 0.7]	0.824	0.2	[-1.2, 1.5]	0.801	0.0	[-1.1, 1.1]	0.977	0.0	[-0.3, 0.4]	0.899
Education	cons = high school												
	certificate/diploma	-3.0	[-17.7, 11.6]	0.685	-10.0	[-33.1, 13.1]	0.397	12.9	[-5.8, 31.6]	0.177	4.3	[-2.1, 10.6]	0.189
	university degree	-1.9	[-16.9, 13.0]	0.799	-15.0	[-38.6, 8.7]	0.215	16.7	[-2.6, 36.0]	0.089	2.6	[-3.9, 9.0]	0.438
Body Mass Index	cons = normal/under												
	overweight	-14.6	[-25.7, -3.6]	0.009	17.1	[-0.7, 34.8]	0.060	-2.1	[-16.8, 12.5]	0.775	-1.7	[-6.4, 3.0]	0.476
	obese	-4.4	[-15.6, 6.9]	0.448	11.8	[-6.2, 29.8]	0.199	-8.6	[-23.4, 6.2]	0.255	-0.7	[-5.5, 4.1]	0.775
Chronic conditions	cons = none												
	one or more	-0.9	[-5.2, 3.4]	0.692	2.3	[-4.5, 9.1]	0.513	-2.2	[-7.8, 3.3]	0.432	0.2	[-1.7, 2.0]	0.864
National physical activity guidelines	cons = below												
	meets	-4.3	[-18.3, 9.6]	0.542	-12.1	[-34.3, 10.1]	0.285	4.4	[-13.6, 22.5]	0.630	4.9	[-1.1, 10.9]	0.108
	exceeds	-7.6	[-21.8, 6.5]	0.290	-8.3	[-30.8, 14.2]	0.470	7.6	[-10.7, 25.9]	0.414	-0.5	[-6.6, 5.5]	0.864
Occupation	cons = none												
	Machinery operators, drivers and labourers	1.4	[-34.3, 37.0]	0.941	19.2	[-37.9, 76.4]	0.510	-26.5	[-73.6, 20.6]	0.271	1.4	[-13.4, 16.1]	0.856
	Community, personal service and sales	-3.6	[-31.5, 24.2]	0.800	34.0	[-11.8, 79.8]	0.146	-29.8	[-68.0, 8.5]	0.127	-1.9	[-13.2, 9.4]	0.740
	Technical and clerical	0.8	[-26.1, 27.8]	0.953	4.6	[-39.8, 49.0]	0.840	2.4	[-34.7, 39.6]	0.898	0.4	[-10.4, 11.3]	0.942
	Managerial and professional	-4.9	[-30.9, 21.0]	0.709	-4.8	[-47.9, 38.4]	0.828	16.5	[-19.9, 52.9]	0.375	0.5	[-9.7, 10.8]	0.917
Shift worker	cons = no												

	yes	-14.3	[-32.3, 3.8]	0.121	21.7	[-6.8, 50.2]	0.136	8.1	[-15.0, 31.2]	0.492	-2.0	[-9.8, 5.8]	0.617
Weekend worker	cons = no												
	yes	3.8	[-10.0, 17.6]	0.588	-15.0	[-36.9, 7.0]	0.182	2.7	[-15.3, 20.7]	0.768	2.0	[-4.0, 7.9]	0.511
Work hours per week	cons = none												
	<15hr	6.8	[-23.9, 37.4]	0.666	2.4	[-47.8, 52.5]	0.926	-3.3	[-45.1, 38.5]	0.876	-1.4	[-14.0, 11.1]	0.821
	≥15 to <36hr	20.1	[-7.5, 47.7]	0.153	-1.9	[-48.0, 44.2]	0.935	-21.9	[-60.8, 17.0]	0.271	-2.4	[-13.2, 8.4]	0.664
	≥36hr (full-time)	16.5	[-10.0, 43.0]	0.223	-9.2	[-53.9, 35.4]	0.685	-15.2	[-53.1, 22.7]	0.433	2.2	[-8.1, 12.4]	0.679

Notes: Results of multi-level mixed-effects linear regression analyses shown. One model per movement behaviour (column). All changes relative to pre-vacation (14-days immediately prior to vacation). Coeff = coefficient (relative to characteristic cons value), cons = constant (comparator / y- intercept), CI = confidence interval, LPA = light physical activity, MVPA = moderate-to-vigorous physical activity. P-values presented above are pre- Bonferroni correction. After correction, no p-values were significant ($p<0.05$).