24-hour movement behaviours in adolescents living with type 1 diabetes: Balancing Healthy Days

by

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Doctoral Thesis

Submitted to the University of Strathclyde in partial fulfilment of the requirements for the award of Doctor of Philosophy in the department of Psychology

2026

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Declaration of contribution to thesis

For each of the studies presented in this thesis, most of the work is directly attributable to the PhD student. Supervisors and co-authors have been involved in the formulation of research ideas and in editing manuscripts. All investigations, analyses and reporting have been carried out solely by the named PhD student, in keeping with the requirements of the degree of doctorate of philosophy in psychology.

For the actigraphy data used in studies two and three, the initial analysis was undertaken by Dr James Sanders (Loughborough University, School of Sport, Exercise and Health Science), who applied the appropriate 24-hour methods in R. This work was necessary due to the limitations of the cut-point approach originally attempted by the PhD student. The PhD student subsequently met with Dr Sanders to review and understand the analytical procedures, ensuring that the methods, outputs and interpretation were fully understood and accurately integrated into the quantitative and qualitative findings presented in this thesis.

Signed:

Date: 27/04/26

Acknowledgements

First and foremost, I want to thank my supervisors. Your support has shaped every aspect of this journey. You helped me become a better researcher and showed me the importance of maintaining a healthy balance between work and life. I truly believe that my PhD has been so enjoyable (even during a global pandemic) because of your unwavering support, humour, and kindness.

To the staff within the University of Strathclyde Psychology and Physical Activity for Health groups, thank you for the professional support, intellectual stimulation, and encouragement throughout this process. I also want to thank my colleagues at **sport**scotland for supporting my PhD completion alongside full-time work.

To my friends and family, thank you for reading drafts, listening to countless practice presentations, and never tiring of hearing about my research (even when you were definitely tired of hearing about my research). You've been patient, uplifting, and a constant source of joy throughout my PhD, helping me stay grounded and smiling.

Finally, to my sport athletics. Thanks to the coaches who kept the sessions flowing, even when my head was buried in writing. Athletics has always been my constant, and throughout this PhD, it's helped me keep perspective (and sanity).

Thesis abstract

Background: Adolescents living with type 1 diabetes (T1D) must manage their condition across the entire 24-hour day. How adolescents combine physical activity (PA), sedentary behaviour (SB), and sleep throughout the day, referred to collectively as 24-hour movement behaviours (24-h MBs), can influence health and wellbeing outcomes. This thesis aimed to explore 24-h MBs in adolescents living with T1D and how such an approach might be understood and applied. **Methods:** This thesis presents three interconnected studies. Study one presents a mixed methods systematic review and meta-analysis synthesising existing evidence on the relationships between PA, SB, and sleep with glycaemic control and psychosocial outcomes in adolescents living with T1D. Study two employed a micro-longitudinal design using wrist-worn accelerometery to objectively assess 24-h MBs in a sample of UK adolescents living with T1D (n=28), with additional self-reported data on HbA1c and diabetes-specific quality of life. Study three was a qualitative investigation involving semi-structured interviews (n=15) with adolescents living with T1D to explore their lived experiences, beliefs, and perceptions of 24-h MBs and their interactions with diabetes self-management. **Results:** The systematic review (n=84 studies) identified a favourable association between PA and glycaemic control, but limited and inconsistent findings for SB and sleep. Critically, no studies examined these behaviours in combination, nor explored their interaction. The accelerometery study (n=28) revealed low compliance with moderate to vigorous physical activity (MVPA) and sleep guidelines and high levels of SB. Although no statistically significant associations were found between movement behaviours, HbA1c and quality of life, trends suggested potential benefits of higher MVPA and longer sleep duration. The qualitative study (n=15) found that adolescents recognised the interconnection of 24-h MBs and linked them to mood, glycaemic control, and their broader environments (i.e., school routines, caregiver support). **Conclusion:** To the author's knowledge, this is the first thesis to apply the 24-h MB paradigm to adolescents living with T1D. The findings from this thesis have informed updates to international clinical guidance and contributes new evidence to the field. This work serves as a foundation for future 24-h MB intervention development specific to this population aiming to improve health outcomes by promoting balance across each 24-h MB, rather than targeting behaviours in isolation.

List of abbreviations

24-h MB – 24-hour Movement Behaviours

ACME Model – Audience, Channel, Message, Evaluation Model

ADA – American Diabetes Association

AIDA Model – Attention, Interest, Desire and Action Model

ASAQ – Adolescent Sedentary Activity Questionnaire

CGM – Continuous Glucose Monitor

CoDA – Compositional Data Analysis

CVD – Cardiovascular Disease

DCCT – Diabetes Control and Complications Trial

DKA – Diabetic Ketoacidosis

DLW – Doubly Labelled Water

ECG – Electrocardiography

EDIC – Epidemiology of Diabetes Interventions and Complications

EEG – Electroencephalography

EMG – Electromyography

ENMO – Euclidean Norm Minus One

EOG – Electrooculography

FITT – Frequency, Intensity, Time, Type

FPG – Fasting Plasma Glucose

GPPD – The Global Platform for the Prevention of Autoimmune Diabetes

HbA1c – Glycated Haemoglobin

HRQoL – Health Related quality of life

IDDM – Insulin Dependent Diabetes Mellitus

IFG – Impaired Fasting Glucose

IGT – Impaired Glucose Tolerance

IPAQ-A – International Physical Activity Questionnaire for Adolescents

ISPAD – International Society for Paediatric and Adolescent Diabetes

ITAD – The Interleukin-2 Therapy of Autoimmunity in Diabetes

LPA – Light Physical Activity

MET – Metabolic Equivalents

MPA – Moderate Physical Activity

MRC – Medical Research Council

MVPA – Moderate to Vigorous Physical Activity

NHANES – National Health and Nutrition Examination Survey

NICE – National Institute for Health and Care Excellence

NIDDM – Non-Insulin Dependent Diabetes Mellitus

NIHR – National Institute for Health Research

NSF – National Sleep Foundation

OGTT – Oral Glucose Tolerance Test

PA – Physical Activity

PedsQL – Paediatric Quality of Life

POINT – The Primary Oral Insulin Trial

PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-analyses

PSG – Polysomnography

PSQI – Pittsburgh Sleep Quality Index

RCT – Randomised Controlled Trial

RPG – Random Plasma Glucose

SB – Sedentary Behaviour

SED – Sedentary Time

SPT-window – Sleep Period Time Window

T1DM – Type One Diabetes Mellitus

T1DUKIC – Type 1 Diabetes UK Immunotherapy Consortium

T2DM – Type Two Diabetes Mellitus

TEDDY – The Environmental Determinants of Diabetes in the Young

UNICEF – United Nations Children’s Fund

VPA – Vigorous Physical Activity

VVPA – Very Vigorous Physical Activity

WHO – World Health Organization

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Summary of thesis outputs

Publications and manuscripts from this thesis

Study 1 (Chapter 2)

Patience, M., Janssen, X., Kirk, A., McCrory, S., Russell, E., Hodgson, W., & Crawford, M. (2023). 24-hour movement behaviours (physical activity, sedentary behaviour and sleep) association with glycaemic control and psychosocial outcomes in adolescents with type 1 diabetes: a systematic review of quantitative and qualitative studies. *International Journal of Environmental Research and Public Health*, *20*(5), 4363 (DOI: https://doi.org/10.3390/ijerph20054363).

Note: The findings from this systematic review informs current clinical practice recommendations for diabetes care. The work is cited in The American Diabetes Association (ADA) Standards of Care in Diabetes for 2023-25 (DOI: https://doi.org/10.2337/dc25-S005).

Study 2 (Chapter 4)

Patience, M., Kirk, A., Janssen, X., Sanders, J., & Crawford, M. (2025). Levels of 24-hour movement behaviours in adolescents living with type 1 diabetes.
[Manuscript prepared for submission to Diabetic Medicine]

Study 3 (Chapter 5)

Patience, M., Kirk, A., Janssen, X., Sanders, J., & Crawford, M. (2025). “If You Haven’t Slept a Lot (…) You Don’t Want to Go Out for a Run, You Don’t Want to Ride a Bike, You Just Kind of Sit and You Just (…) Do Nothing”—Perceptions of 24-Hour Movement Behaviours Among Adolescents Living with Type 1

Diabetes. *International Journal of Environmental Research and Public Health*, *22*, 1295 (DOI: https://doi.org/10.3390/ijerph22081295)

Book Chapters

Fleming, L., Crawford, M., Martin, B., **Patience, M.,** & Fisher-Hicks, S. (2025). Sleep and medical disorders. In Colin A. Espie, Phyllis C. Zee, and Charles M. Morin (eds), *The Oxford Handbook of Sleep and Sleep Disorders*, 2nd edn, Oxford Library of Psychology

Publications not related to this thesis

Russell, E., Kirk, A., Dunlop, M. D., Hodgson, W., **Patience, M.,** & Egan, K. (2025). Digital Physical Activity and Sedentary Behavior Interventions for Community-Living Adults: Umbrella Review. *Journal of medical Internet research*, *27*, e66294.

Conference abstracts from this thesis (published)

Patience, M., Janssen, X., Kirk, A., & Crawford, M. (2021). 22 24-hour movement behaviours (physical activity, sedentary behaviour and sleep) impact on adolescents physiological and psychosocial adaptation to type 1 diabetes: a mixed methods systematic review. *BMJ Open Respiratory Research 8(Suppl 1): A10-A12* (DOI:10.1136/bmjresp-2021-bssconf.19).

Conference abstracts from this thesis (not published)

Patience, M., Kirk, A., Janssen, X., Sanders, J & Crawford, M. (2024) Comparison of adolescents with type 1 diabetes 24-hour movement behaviours to the Canadian 24-hour movement behaviour guidelines. (Presented at the Diabetes UK Professional Conference 2024, London, England).

Patience, M., Kirk, A., Janssen, X., & Crawford, M. (2024) Perceptions of 24-hour Movement Behaviours in Adolescents with Type 1 Diabetes: A Qualitative Study. (Presented at the International Pediatric Sleep Association Conference 2024, Glasgow, Scotland).

Patience, M., Kirk, A., Janssen, X., Sanders, J & Crawford, M. (2024) Adolescents with Type 1 Diabetes Perceptions of 24-Hour Movement Behaviours: A Mixed Methods Study. (Presented at the European College of Sport Science Conference 2024, Glasgow, Scotland).

Conference presentations from this thesis

2024

Patience, M., Kirk, A., Janssen, X., Sanders, J & Crawford, M. (2024) Comparison of adolescents with type 1 diabetes 24-hour movement behaviours to the Canadian 24-hour movement behaviour guidelines. (Poster presented at the Diabetes UK Professional Conference 2024, London, England).

Patience, M., Kirk, A., Janssen, X., & Crawford, M. (2024) Perceptions of 24-hour Movement Behaviours in Adolescents with Type 1 Diabetes: A Qualitative Study. (Poster presented at the International Pediatric Sleep Association Conference 2024, Glasgow, Scotland).

Patience, M., Kirk, A., Janssen, X., Sanders, J & Crawford, M. (2024) Adolescents with Type 1 Diabetes Perceptions of 24-Hour Movement Behaviours: A Mixed Methods Study. (Poster presented at the European College of Sport Science Conference 2024, Glasgow, Scotland).

Patience, M., Kirk, A., Janssen, X., Sanders, J & Crawford, M. (2024) Perceptions of 24-Hour Movement Behaviours in adolescents living with type 1 diabetes. (Oral presentation at the Scottish Physical Activity Research Connections (SPARC) Conference 2024, Edinburgh, Scotland).

2023

Patience, M., Kirk, A., Janssen, X., & Crawford, M. (2023) 24-hour Movement Behaviours in Adolescents with Type 1 Diabetes, Recruitment of Adolescents within Clinical Populations. (Oral presentation at the Scottish Physical Activity Research Connections (SPARC) Conference 2024, Edinburgh, Scotland).

2021

Patience, M., Kirk, A., Janssen, X., & Crawford, M. (2021) 22 24-hour movement behaviours (physical activity, sedentary behaviour and sleep) impact on adolescents physiological and psychosocial adaptation to type 1 diabetes: a mixed methods systematic review. (Poster presented at the British Sleep Society Conference 2021, Online Event).

Awards from this thesis

Best Academic Oral Presentation, Scottish Physical Activity Research Connections (SPARC) Conference 2024

Shortlisted entrant for the Paediatric Diabetes Award, Diabetes UK Professional Conference 2024

Shortlisted entrant of Research competition, University of Strathclyde

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Chapter 1 - Introduction

1. Chapter Overview

This chapter aims to give an overview of the key components explored within this research, specifically, type 1 diabetes (T1D), adolescents and 24-hour movement behaviours (24-h MBs; physical activity, sedentary behaviour and sleep). Following the introductions of all key elements, 24-h MBs will be directly explored in relation to adolescents living with T1D. The chapter will finish by clearly stating the aims of the thesis and structure. Please Note: The landscape of T1D is rapidly evolving with advances in diagnostic approaches, immunotherapies and diabetes technologies significantly altering disease management and risk profiles. As such, conclusions based on historical data should be made with caution as the field continuous to advance.

2. Introduction to diabetes

2.1 Definition and fundamental physiology

Diabetes Mellitus, simply referred to as ‘Diabetes,’ describes a group of metabolic disorders in which there is a deficiency in the secretion and/or action of the hormone insulin. This results in chronic high blood glucose levels (hyperglycaemia), which is the defining characteristic of diabetes (World Health Organization, 2019). In individuals without diabetes, the body regulates glucose levels within narrow boundaries through the complex interplay of a variety of hormones. The key hormones in glucose regulation are insulin, produced by beta cells (β-cells) in the pancreas to lower blood glucose in response to hyperglycaemia, and glucagon, produced by α-cells in the pancreas to raise blood glucose in response to hypoglycaemia (low blood glucose levels) (Aronoff, Berkowitz, Shreiner, & Want, 2004). Glucose levels fluctuate constantly throughout the 24-hour period requiring these hormones to consistently function efficiently. However, in those with diabetes, the dysfunction or destruction of pancreatic β-cells causes insulin deficiency and treatment is required to ensure successful blood glucose regulation (Schwartz et al., 2016; Skyler et al., 2017).

2.2 Prevalence and economic impact of diabetes

Diabetes is a highly prevalent condition globally, contributing to high mortality rates and economic spending. In 2024, an estimated 589 million individuals were living with diabetes with numbers projected to rise to 853 million by 2050 and the number adults estimated to have died in 2024 due to diabetes and associated complications was estimated to be 3.4 million (International Diabetes Federation, 2025). Additionally, the estimated annual global health expenditure due to diabetes in 2024 was US$1.015 trillion and expected to increase to $1.043 trillion by 2050 (International Diabetes Federation, 2025). There are several types of diabetes however, Type 2 (T2DM) and Type 1 Diabetes Mellitus (T1DM) are the most common forms.

2.3 Type 2 diabetes mellitus

T2DM is caused by several levels of β-cell dysfunction and insulin resistance by cells (Kahn, Cooper, & Del Prato, 2014) and is the most common form of diabetes, accounting for 90% of all cases globally (International Diabetes Federation, 2025). T2DM has previously been referred to as ‘adult-onset diabetes’ due to the greater prevalence of the condition in adults. However, there are now increasing numbers of children and adolescents living with the condition (World Health Organization, 2016). This contributes to the current rise in the global prevalence of

T2DM which is symptomatic of an ageing population and the ever-increasing global rates in obesity, due to changes in lifestyle factors (e.g. increased sedentary time and consumption of unhealthy food) affected by economic and urbanisation developments (Basu, Yoffe, Hills, & Lustig, 2013).

T2DM has also often been referred to as ‘non-insulin dependent diabetes mellitus’ (NIDDM) because insulin is not crucial to survival or the management of the condition. Instead T2DM can be managed by adopting positive lifestyle behaviours (e.g. healthy diet, physical activity, smoking cessation and maintenance of a healthy body weight) and this is the initial management strategy given the high prevalence of obesity in those with T2DM. Failing the adoption of positive lifestyle behaviours blood glucose levels can be controlled using oral medication and - although uncommon and contradictory to the NIDDM term - insulin can be administered to bypass complications if the condition worsens (International Diabetes Federation, 2025).

2.4 Type 1 diabetes mellitus

T1DM is caused by an ‘autoimmunity’ process, where cells within the body attack the β-cells in the pancreas resulting in absolute insulin deficiency (Pihoker, Gilliam, Hampe, & Lernmark, 2005). T1DM is also referred to as ‘insulin-dependent diabetes mellitus’ (IDDM) as daily insulin is crucial to survival and the management of the condition. Insulin regimes are often specific to the individual and vary by insulin type, daily frequency of insulin administration and delivery methods (Maahs, West, Lawrence, & Mayer-Davis, 2010). Constant monitoring throughout the 24-hour period of both blood glucose levels and lifestyle factors influencing glucose levels (e.g. diet and physical activity) are required to ensure the correct level of insulin is administered (American Diabetes Association, 2018). The use of technology greatly facilitates glucose level monitoring (meters or continuous glucose monitors) and insulin administration (pens, syringes or pumps) and are developing rapidly with some hybrid devices capable of simultaneously monitoring glucose levels and delivering insulin accordingly, otherwise known as an 'artificial pancreas' (American Diabetes Association., 2020). T1DM technology will continue to improve throughout the course of time and provide an invaluable tool to manage the condition over the 24-hour period (Avari, Reddy, & Oliver, 2020). However, the use of healthy lifestyle behaviours should not be considered obsolete in this new technological era as they also aid in the management process, including preventing longer term complications and promoting a number of physical, psychological and social benefits. Instead, T1DM technology and healthy lifestyle behaviours should work in unison to optimise T1DM management and ultimately improve T1DM outcomes.

Investigation into T1DM risk factors is a crucial area of study for many researchers in the field as they try to reduce or reverse the growing prevalence. Evidence has established the vital role genetics play in developing T1DM (Krischer et al., 2015; Parikka et al., 2012; Ziegler, Bonifacio, & Group, 2012) however, environmental risk factors are additionally thought to play a role in developing the condition through complex gene-environment interactions (Rewers & Ludvigsson, 2016). A number of T1DM pathogenesis hypothesis (e.g. the accelerator, hygiene and β-cell stress hypothesis) and potential environmental risk factors have been proposed throughout the years to explain the rise in T1DM prevalence however, few have been consistently confirmed. In an attempt to consolidate hypotheses and potential risk factors and facilitate the movement toward T1DM primary prevention, international networks following children at high T1DM risk have been created including a major prospective cohort study created in 2003, The Environmental Determinants of Diabetes in the Young (TEDDY) (Rewers et al., 2018). The more widely accepted environmental risk factors for triggering T1DM autoimmunity are infection during pregnancy and childhood (Allen, Kim, Rawlinson, & Craig, 2018; Lonnrot et al., 2017; Yeung, Rawlinson, & Craig, 2011) introduction of foreign antigens through infant diet (Hummel et al., 2017; Norris et al., 2003; Ziegler, Schmid, Huber, Hummel, & Bonifacio, 2003) and rapid growth and weight gain in early life (Couper et al., 2009; Ferrara et al., 2017; Larsson et al., 2016). Environmental factors that may have a protective effect include high levels of omega 3 fatty acids during infancy (Niinisto et al., 2017; Norris et al., 2007), vitamin D sufficiency (Norris et al., 2018) and exposure to probiotics during early infancy (Uusitalo et al., 2016). The evidence underpinning the aforementioned environmental associations is derived largely from observational studies which are inherently limited in their ability to establish causality. Furthermore, inconsistencies across cohorts and relatively modest effect sizes suggest that these factors are unlikely to act in isolation but instead within complex gene-environment interactions. While these findings contribute valuable insight into potential mechanisms, they should be interpreted with caution.

Although there is currently no known cure for T1DM, the use of immunotherapies is gaining significant traction. Immunotherapies aim to train the immune system to stop the destruction of pancreatic β-cells and is currently under investigation for T1DM prevention (prevent or delay β-cell functional decline), treatment (preserve β-cell function) and even cure (adjuvant therapy in islet cell transplantation) (Coppieters & von Herrath, 2018). Recently, consortiums of research institutions investigating immunotherapies in T1DM have been established. The Global Platform for the Prevention of Autoimmune Diabetes (GPPAD) was created in 2015 and are currently conducting a large-scale primary prevention randomised controlled trial (RCT) named the Primary Oral Insulin Trial (P-OiNT). The P-OiNT study enrols new-borns and infants (4–7 months) who are at increased risk of T1DM and uses immunotherapy, in the form of daily oral insulin, until the age of 3-years aiming to determine if β-cell functional decline can be prevented or delayed (Ziegler et al., 2019). Similarly, in the United Kingdom the Type 1 Diabetes UK Immunotherapy Consortium (T1DUK) was created in 2015 to promote, develop and support immunotherapy T1DM clinical trials. Thus far, a range of immunotherapy clinical trials are underway in children and adolescents (6–18 years) recently diagnosed with T1DM (within 100 days). The aim of these studies is to maintain remaining β-cell function and maximise insulin production. Examples of T1DUK immunotherapy trials include, the Interleukin-2 Therapy of Autoimmunity in Diabetes (ITAD) Study (6–18 years), Ustekinumab in Adolescents with New Onset Type 1 Diabetes (USTEKID Study Trial) (12–18 years) and the PROTECT study (8–17 years).

2.5 Signs, symptoms, diagnosis tests and criteria

Hyperglycaemia is the clinical indicator of diabetes, and four diagnostic tests are currently recommended (**Table 1.1**). These diagnostic tests are based on international guidelines and apply to diabetes broadly (International Diabetes Federation, 2025). In clinical practice, differentiation of diabetes type requires additional information beyond glycaemic thresholds. The diagnosis of T1D is facilitated by an acute onset of symptoms, including excessive thirst, distorted vision, frequent urination, lack of energy, continuous hunger and rapid weight loss. These symptoms are commonly communicated as the ‘4 Ts’ (thirst, toilet, tiredness, thinner). Additionally, the presence of DKA and autoantibodies supports a diagnosis of T1D and helps distinguish it from T2D (International Diabetes Federation, 2025).

Table 1.1: Diagnosis criteria for diabetes (Informed by the International Diabetes Federation, 2025).

Test	**Diabetes** (≥1 criteria met)[a]	**Impaired Glucose Tolerance (IGT)** (if both criteria met)	**Impaired Fasting Glucose (IFG)** (if FPG or both criteria met)
Fasting Plasma Glucose (FPG)[b]	≥ 7.0 mmol/L (≥ 126 mg/dL)	< 7.0 mmol/L (126 mg/dL)	6.1–6.9 mmol/L (110–125 mg/dL)
Two-Hour Plasma Glucose (OGTT) (post 75g oral glucose load)	≥ 11.1 mmol/L (≥ 200 mg/dL)	≥ 7.8 and < 11.1 mmol/L (140–199 mg/dL)	< 7.8 mmol/L (140 mg/dL)
HbA1c[c]	≥ 48 mmol/mol (≥ 6.5%)	-	-
Random Plasma Glucose (RPG) (with hyperglycaemia symptoms)	≥ 11.1 mmol/L (≥ 200 mg/dL)	–	–

[a]In the absence of symptoms of hyperglycaemia, two abnormal tests are required for the diagnosis of diabetes.
[b]Fasting is defined as no caloric intake for at least 8 hours.
[c]The HbA1c test reflects average blood glucose over ~90 days and must be performed using a certified method.

2.6 Complications of diabetes

A number of complications arise from diabetes if blood glucose levels are not maintained sufficiently. Acute complications are more common in T1DM than T2DM, specifically diabetic ketoacidosis (DKA) (Rohwerder et al., 2022), where there is an accumulation of ketones in the body requiring expert management and treatment to bypass permanent neurological consequences or death (Wolfsdorf et al., 2018). Additionally, severe hypoglycaemia can occur and requires treatment with glucagon or glucose to avoid serious outcomes such as a seizure or coma (Abraham et al., 2018).

Macrovascular (large blood vessels) and microvascular (small blood vessels) complications can occur from poor blood glucose control in both T1DM and T2DM however, is more frequent in T1DM. These complications can result in detrimental consequences. Macrovascular complications increase the risk of cardiovascular disease (CVD), specifically, coronary heart disease, cerebrovascular disease, peripheral heart disease and congestive heart failure and is the largest cause of morbidity and mortality for individuals with diabetes (Gerstein, 2015). Microvascular complications include retinopathy, nephropathy and neuropathy. Retinopathy affects the eyes and is one of the leading causes of blindness globally (Lee, Wong, & Sabanayagam, 2015). Nephropathy affects the kidneys and often results in chronic kidney disease, especially when coupled with hypertension (Saran et al., 2018). Neuropathy affects the nerves of limbs causing unusual feelings and numbness potentially resulting in chronic ulcers and amputation which can significantly reduce quality of life (Zhang et al., 2017).

The detrimental consequences of diabetes complications initiated the implementation of the Diabetes Control and Complications Trial (1982–1993; DCCT), a pioneering study designed to test the ‘glucose hypothesis’ which stated the long-term microvascular and neurological complications of T1DM would improve by achieving near normal blood glucose levels. The DCCT had two overarching aims, to determine if an intensive insulin therapy (≥3 daily insulin injections or treatment with an insulin pump) compared to conventional therapy (1–2 daily insulin injections) would 1) prevent retinopathy development and 2) affect the negative progression of early retinopathy. Additionally, renal, neurologic, cardiovascular and neuropsychological outcomes were measured. Otherwise, healthy individuals (13–39 years) (n=1441) with diagnosed T1DM were split into a primary prevention cohort, who had a duration of 1–5 years of diagnosis with no evidence of retinopathy, and a secondary intervention cohort with a duration of 1–15 years of diagnosis with mild-moderate evidence of retinopathy. After 6.5 years of the studies duration, a mean of 7% HbA1c was reported in the intensive group compared to a mean of 9% HbA1c in the conventional group. Intensive therapy delayed the onset of retinopathy, nephropathy and neuropathy by 34–76% compared to the conventional therapy with a rate of complication progression ranging between 0.2–3.1 per 100 patients per year compared to a rate of progression ranging between 0.3–9.8 per 100 patients per year in the conventional group. Similarly, the intensive therapy slowed the progression of retinopathy, nephropathy and neuropathy by 23–57% compared to conventional therapy with a rate of complication progression ranging between 0.6–7.0 per 100 patients per year compared to a rate of progression ranging between 1.4–16.1 per 100 patients per year in the conventional group (The Diabetes Control and Complications Trial Research Group, 1993).

The success of the DCCT resulted in a large scale observational follow up study (1994 - present) named the Epidemiology of Diabetes Interventions and Complications (EDIC) to determine the maintenance of the DCCT intensive treatment effects on retinopathy and nephropathy for 4-years after the DCCT. The EDIC used the same DCCT cohort ensuring all participants (n=1302) were offered the original intensive therapy training and previous diabetes care were restored to each participants own physicians. This resulted in the disappearance of the DCCT HbA1c group differences within the first 4-years of the EDIC follow up (median of 8% in each group). However, in the initial intensive therapy group, progression of retinopathy risk was reduced by 60–83% and worsening of pre-existing retinopathy and nephropathy risk was reduced by 53–92% compared to the conventional therapy group (The Diabetes Control and Complications Trial Research Group/Epidemiology of Diabetes Interventions and Complications Research Group, 2000). Moreover, a subsequent study investigated the DCCT group (n=1397) effects on the long-term incidence of CVD at 17 years follow up and reported the initial intensive treatment reduced the risk of CVD events by 42% and the risk of myocardial infarction, stroke or death from CVD by 57% compared to the conventional group (The Diabetes Control and Complications Trial Research Group/Epidemiology of Diabetes Interventions and Complications Research Group, 2000).

The aforementioned DCCT and EDIC studies validated the glucose hypothesis and confirmed interventions aiming to manage blood glucose levels to near normal ranges reduced both the microvascular and macrovascular complications of T1DM. Additionally, these studies highlight a durable effect on complications from early glycaemic control, a phenomenon now referred to as 'metabolic memory.' These findings have been transferred into real world clinical settings where intensive treatment regimens are implemented at initial diagnosis to improve the long-term health of individuals with T1DM and the EDIC follow-up study continues to provide a key extant resource to inform T1DM management (Nathan, 2014).

2.7 Technology and type 1 diabetes

The pioneering DCCT/EDIC studies established HbA1c as the gold standard measure in assessing glycaemic control and related risk of long-term micro and macrovascular complications (The Diabetes Control and Complications Trial Research Group, 1993). However, HbA1c only provides an average level of blood glucose over the past 2–3 months and little information can be ascertained regarding the frequency, duration or amplitude of intra-day (within-day) and inter-day (between-day) glycaemic excursions (Beck, Connor, Mullen, Wesley, & Bergenstal, 2017; Danne et al., 2017). Continuous glucose monitors (CGMs) have increased in availability and accuracy over the last century and have facilitated diabetic glycaemic control. They produce real-time measurements of the glucose level excursions HbA1c overlooks, allowing for immediate action to address raised or lowered glucose levels that can subsequently prevent potential acute incidents (e.g. hypoglycaemia and hyperglycaemia). Additionally, information from CGMs allow individuals, clinicians and others involved to make educated choices regarding appropriate medication and other daily diabetes self-management behaviours based on glucose profiles and trends (Galindo & Aleppo, 2020).

The value of CGMs for glycaemic control has been recognised widely, resulting in standardised metrics and targets to guide clinicians, patients and researchers in using, analysing, and reporting CGM data to comprehensively assess glycaemic control (Battelino et al., 2019; Danne et al., 2017). However, access to CGM technology remains variable and disparities in availability may influence both uptake and outcomes. Therefore, while CGMs represent a significant advancement in diabetes management their impact should be interpreted considering CGM availability.

3. Adolescents and type 1 diabetes

3.1 Introduction to adolescence

The definition of adolescence varies widely across the literature, globally recognised organisations such as the World Health Organisation (WHO) and the United Nations Children's Fund (UNICEF) defines adolescents as individuals aged between 10 and 19 years, while others extend this age range to 10 and 24 years, acknowledging the prolonged transition to adulthood in many societies (Patton & Temmerman, 2016; Patton et al., 2016). Adolescence derives from the Latin *adolescere,* which means to grow up. It represents the stage of life bridging between childhood and adulthood. It encompasses complex biological, psychological and behavioural changes which are all influenced by social, cultural and geographical factors (Sawyer, Azzopardi, Wickremarathne, & Patton, 2018).

In western countries, obesity rates are steadily increasing in this age group which is a key risk factor in the development of chronic disease (Abarca-Gomez (Abarca-Gómez et al., 2017; Guthold, Stevens, Riley, & Bull, 2020). Additionally, the mental health of adolescents presents one of the greatest health issues for this population where half of adult mental health disorders develop by age 14 (Gore et al., 2011; Kessler et al., 2007). Due to the number of changes adolescents begin to undergo and the multitude of factors that shape these changes it is crucial that healthy patterns of behaviour are supported through information and opportunity. This is especially important considering behaviours contributing to physical and mental health track strongly into adult life (Jackson, Henderson, Frank, & Haw, 2012).

3.2 Adolescents living with type 1 diabetes

T1D is the major type of diabetes in children and adolescents but can occur at any age. In 2024, the total number of children and adolescents (0–19 years) living with T1DM globally was 1.81 million, representing 19.8% of the total population living with T1D (International Diabetes Federation, 2025). Adolescence marks a period of significant change for individuals which can be difficult to navigate, and this critical developmental stage can be especially complicated for those living with T1D due to additional physiological, emotional, social and familial factors associated with the condition. During adolescence, individuals undergo significant hormonal changes associated with puberty, which can lead to increased insulin resistance and fluctuations in blood glucose levels (Zhu, Volkening, & Laffel, 2019). These physiological changes make it difficult for adolescents to maintain stable glycaemic control, as their bodies may respond unpredictably to insulin and dietary intake (Zhu et al., 2019). Additionally, adolescents living with T1D often experience significant emotional and mental health challenges including feelings of isolation, anxiety, diabetes distress and depression which are more prevalent compared to peers without T1D (Bernstein, Stockwell, Gallagher, Rosenthal, & Soren, 2013; Brodar, Davis, et al., 2021; Brodar, Hong, et al., 2021). Research indicates that these emotional challenges not only hinder effective diabetes management but can also contribute to poorer overall health outcomes and behaviours such as disordered eating and substance use (Creo et al., 2021; Garner, 2007; Ripoli et al., 2022).

Adolescents with T1D face significant social challenges that can impact their overall well-being and quality of life. The management of T1D often requires adolescents to engage in self-care behaviours that can make them feel different from their peers, leading to feelings of isolation and anxiety about social interactions (Commissariat, Kenowitz, Trast, Heptulla, & Gonzalez, 2016). Many adolescents report a desire to fit in and feel "normal," which can be difficult when they must monitor their blood glucose levels or administer insulin in social settings (Ingersgaard, Hoeeg, Willaing, & Grabowski, 2019). This desire for normalcy can lead to reluctance in performing self-management tasks in front of peers making it more challenging to maintain glycaemic control (Begjani, 2024; Commissariat et al., 2016; Ingersgaard et al., 2019).

The management of T1D often requires substantial involvement from family members however, as individuals transition from childhood to adolescence their level of autonomy increases. This increase in autonomy often results in a transition from parental management to self-management and can create tension within families, leading to feelings of frustration and helplessness among both parents and adolescents (Almeida, Leandro, & Pereira, 2020). Additionally, parental stress and coping strategies directly influence the adolescent's metabolic control, with higher levels of parental stress correlating with poorer glycaemic outcomes (Bassi, Mancinelli, Riso, & Salcuni, 2020; Delamater, Patiño-Fernández, Smith, & Bubb, 2012). Thus, fostering effective communication and support within the family is essential for promoting better health management and emotional well-being in adolescents with T1D (Benson et al., 2023).

3.3 Adolescent adaptation to type 1 diabetes

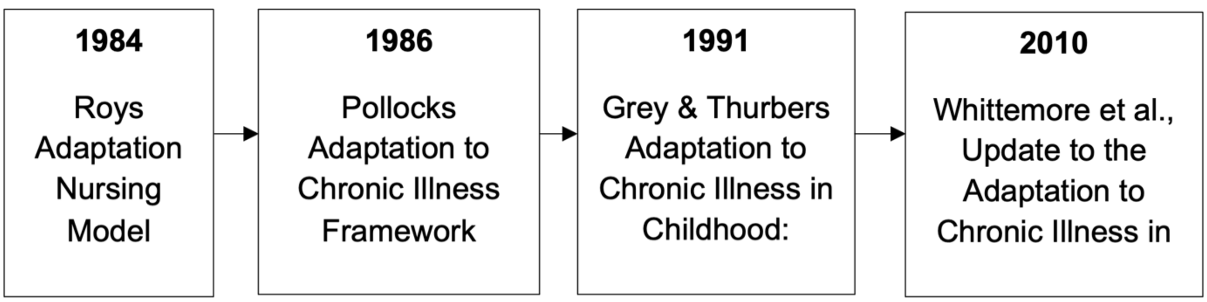
It is clear there are several complex factors present for adolescents living with T1D that must be navigated. Stress-adaptation models provide a framework to promote adaptation to chronic illness and have been revised and modified throughout the years (**Figure 1.1**). These models theorise that adaptation is viewed as an active process where the individual adjusts to the environment and the challenges of a chronic illness (Grey & Thurber, 1991; Pollock, 1986; Roy, 1984; Whittemore, Jaser, Guo, & Grey, 2010).

Whittemore et al. (2010) developed a conceptual model of adaptation to T1D that emphasises the multifaceted nature of adaptation in children and adolescents managing this condition. The model identifies key components that influence adaptation, including individual and family characteristics, psychosocial responses, individual and family responses and adaptation. Individual and family characteristics include age, duration of diabetes, sex, socioeconomic status, race/ethnicity, treatment modality, pubertal development and family environment. Each of these factors influence how effectively adolescents adapt to the challenges of T1D. Psychosocial responses such as depressive symptoms and anxiety/stress are often consequences of living with T1D and the development of psychological problems such as depression, behavioural disorders, and disordered eating can develop over time. These psychosocial responses are mediated by individual and family responses such as coping and self-efficacy, family functioning and social competence and self-management.

The aforementioned sections of this model ultimately affect the ability of adolescents with T1D to adapt to the stress of living with T1D which is marked physiologically by metabolic control and psychosocially by quality of life.

Given the considerable difficulties faced by adolescents and their families, there is a pressing need for holistic innovative approaches that address the intricate physiological, psychosocial, and familial factors that impact positive adaptation to T1D.

Figure 1.1: Timeline of changes to the stress-adaptation model.



4. Introduction to 24-hour movement behaviours

4.1 Movement Behaviour Definitions

PA, SB and sleep are multidimensional behaviours that extend beyond one specific behaviour and are influenced by a range of intrinsic (e.g., genetics) and extrinsic (e.g., environmental) factors. Subcategories of each behaviour are often described and measured in movement behaviour research. Therefore, it is important to understand the core subcategories and principles of these behaviours to effectively appraise the literature. Whether an activity belongs to PA, SB or sleep, ultimately depends on the amount of oxygen required for a given activity (metabolic equivalents or METs).

PA is defined as any “bodily movements” produced by the skeletal muscles that results in an energy expenditure of more than 1.5 metabolic equivalent units [METs] and can be characterised by context/domain (e.g. transportation, occupational, leisure-time and household). A subset of PA is exercise and is defined as PA that is planned, structured, repetitive and results in improvement or maintenance of one or more facets of physical fitness (e.g. cardiorespiratory, metabolic, muscular, morphological or motor) (Casperson, Powell, & Christenson, 1985). Within movement behaviour research the FITT principle is often used to further breakdown PA and stands for frequency (e.g. activity two times per week), intensity (e.g. light, moderate and vigorous activity), time (e.g. 60 minutes of activity per day) and type (e.g. bone-strengthening, aerobic, anaerobic, balance, flexibility, sport) (American College of Sports Medicine, 2014).

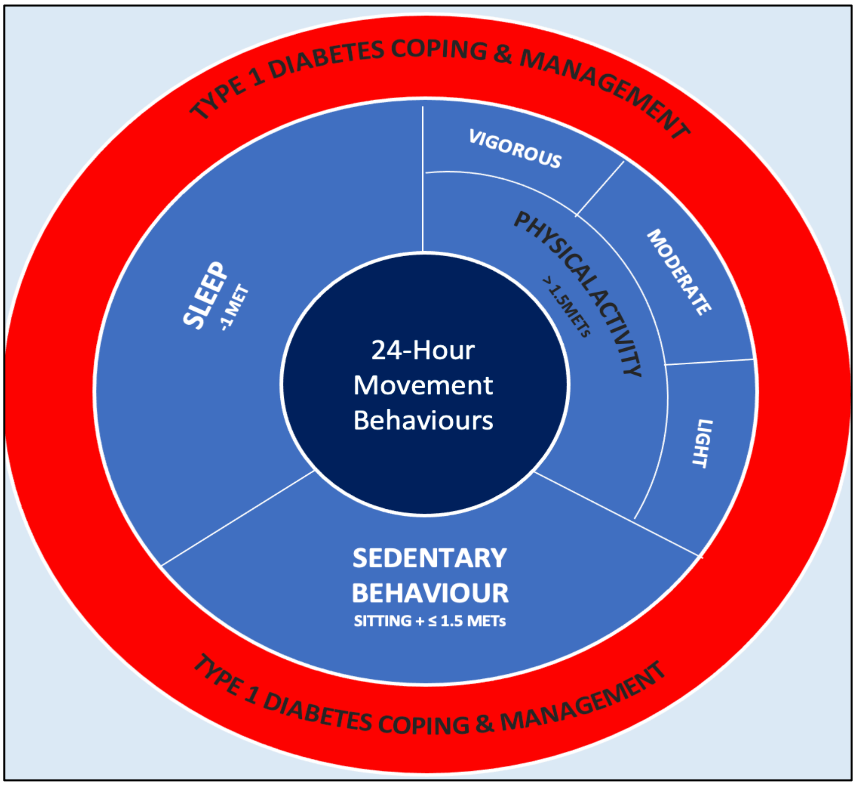
SB is a more recent term within the movement science literature and is defined as any waking behaviour characterised by an energy expenditure of ≤1.5 METs while in a sitting, reclining or lying posture (Tremblay et al., 2017). SB can be performed in a variety of contexts/domains (e.g. occupational, leisure-time, domestic, transportation) and is often combined with other multitasking behaviours (e.g. simultaneous screen time and non-screen time activities). Additionally, SB can be further broken down into overall sedentary time (time spent for any duration or in any context in SB), sedentary bouts (period of uninterrupted sedentary time) and sedentary interruptions/breaks (non-sedentary bout between two sedentary bouts) (Tremblay et al., 2017).

Sleep is a fairly novel area of study within movement behaviour research and is generally defined as a naturally occurring, rhythmic, reversible period of immobility and reduced sensory responsiveness and is characterised by an energy expenditure of ~ 1 METs (Carskadon, 2011; Tremblay et al., 2017). Sleep health is a term that has received recent traction within research, clinical and regulatory environments and has been defined as a multidimensional pattern of sleep-wakefulness, adapted to individual, social and environmental demands, that promotes physical and mental well-being. Six dimensions have been highlighted in relation to sleep health namely, duration (total amount of sleep obtained within the 24-hour period), continuity or efficiency (ease of falling asleep and returning to sleep), timing (when sleep occurs during the 24-hour period), alertness or sleepiness (ability to maintain wakefulness), satisfaction/quality (subjective assessment of a good or poor sleep) and regularity (bedtime and waketime occurring at the same time, within one hour, every day) (Buysse, 2014). While all the sleep health dimensions are important to consider, the duration and quality of sleep-in relation to health has been the main dimensions of focus within movement behaviour research.

4.2 Movement behaviours and health

PA, SB and sleep all have a plethora of established health benefits across all age groups when examined in isolation. PA has been associated with physical, psychosocial, motor skill and cognitive health improvements and reductions in all-cause mortality (Carson et al., 2017; Kraus et al., 2019; Poitras et al., 2016). High amounts of SB have been associated with increased CVD, T2DM and cancer incidence, lower fitness and self-esteem and increased risk of all cause and CVD mortality (Carson et al., 2016; Katzmarzyk et al., 2019; Poitras et al., 2017). Finally, sleep duration has been associated with improved, body composition, emotional regulation, academic achievement, quality of life and childhood growth; and lower, indicators of adiposity, cardiometabolic biomarkers, harms/injuries, cardiovascular events and mortality (Chaput et al., 2017; Chaput et al., 2016; Yin et al., 2017). However, these relationships may not be strictly linear as evidence suggests that PA and sleep can demonstrate U-shaped or curvilinear associations with health, whereby both insufficient and excessive levels are linked to adverse outcomes (Eijsvogels, Thompson & Franklin, 2018; Yin et al., 2017). In contrast, SB is more consistently associated with adverse health outcomes in a dose-response manner. Although its effects may vary depending on the context, type and pattern of accumulation (Tremblay et al., 2017). Collectively, this highlights the complexity of these behaviours and suggests that their health effects may not be fully captured when considered in isolation. Accordingly, there has been a recent paradigm shift in the movement science literature arguing individual movement behaviours for health should no longer be examined in isolation (Pedišić, Dumuid, & Olds, 2017). Instead, an integrated approach should be adopted, where all movement behaviours within the 24-hour day (e.g. sleep, PA and SB) exist as a continuum from no movement (e.g. sleep) to high movement (e.g. vigorous PA (VPA)). These behaviours are considered relative or time-dependent which means a decrease in one behaviour will result in a change in one of the other behaviours. Importantly, the way in which these movement behaviours are combined throughout the day has shown to have significant health implications for all age groups (Rollo, Antsygina, & Tremblay, 2020).

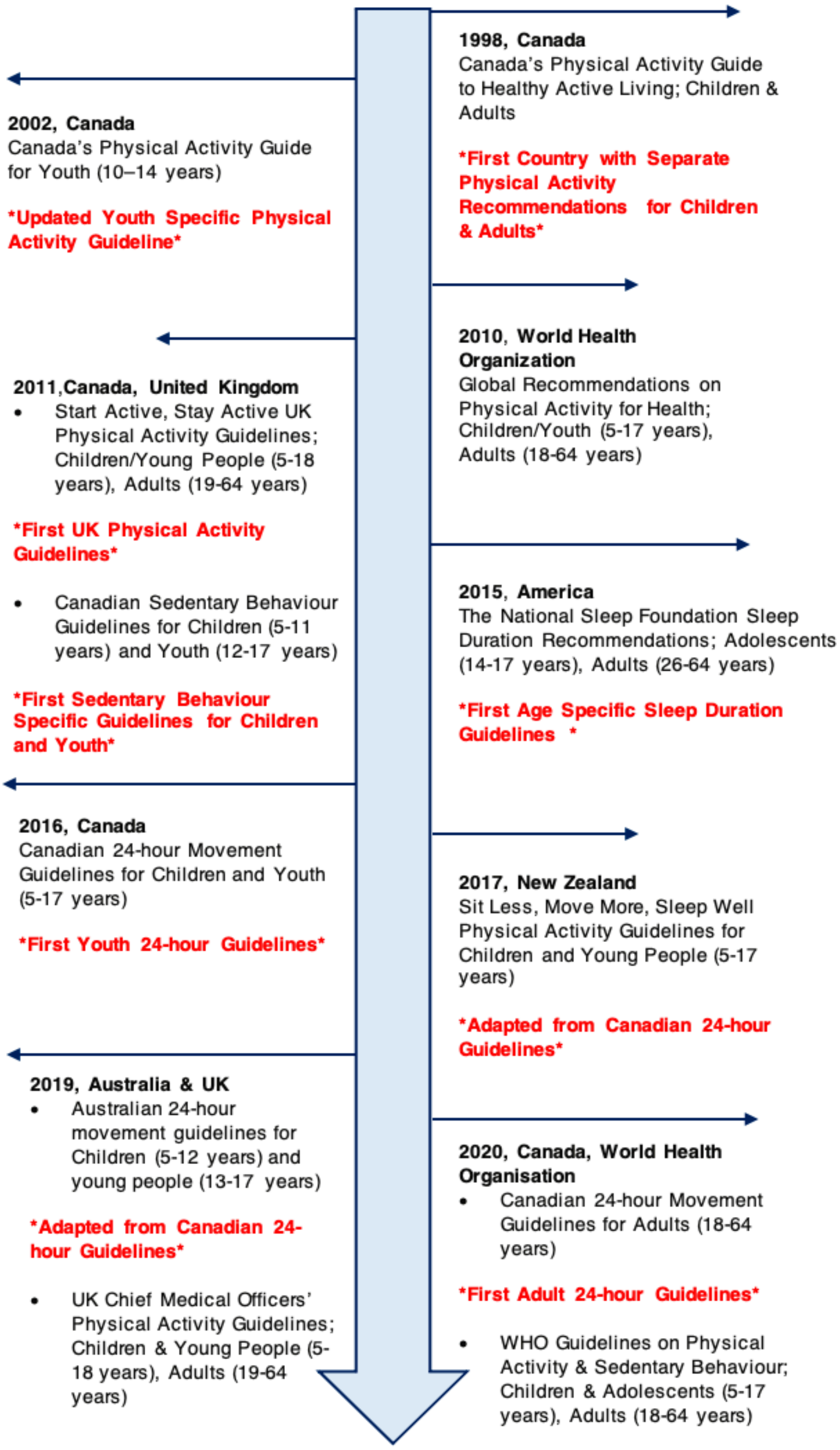
Figure 1.2: 24-hour movement behaviour model and essential type 1 diabetes 24-hour management and coping (adapted from Tremblay et al., 2017, Figure 3)



4.3 Historical development of movement behaviours and health

A plethora of movement behaviour guidelines for health have been developed throughout history, for a range of age groups within a variety of countries however, these go beyond the scope of this research. The movement behaviour guidelines highlighted in this section were selected in relation to pioneering guidelines and 24-h MB guidelines for the adolescents/youth and adult population. **Figure 1.3** presents a visual timeline diagram of the discussed movement behaviour guidelines.

Figure 1.3: Timeline of movement behaviour guideline development.



Canada has historically been a pioneering country in movement behaviour guideline development. In 1998, Canada created the first PA guideline with separate recommendations for both children and adults, which additionally included the first ever recommendation to reduce SB (Canada's Physical Activity Guide to Healthy Active Living). Canada continued to advance PA guideline development and released a new guideline in 2002 dedicated solely to the requirements of children (6-years) and youth (10–14 years) (McCrorie, Martin, & Janssen, 2020). A range of countries quickly followed Canadas lead in developing separate youth and adult PA recommendations and in 2010, the World Health Organization (WHO) created the first global PA guidelines for all age groups. The Global Recommendations on PA for Health recommended children and youth (5–17 years) participate in at least 60 minutes or more of mainly moderate to vigorous PA (MVPA) each day with incorporated VPA including muscle and bone strengthening exercises at least 3 times per week. Additionally, adults (18–64 years) were recommended to participate in at least 150–300 minutes of moderate aerobic or at least 75–150 minutes of vigorous aerobic PA each week, or a combination of both, in bouts of 10-minute activity and incorporating muscle strengthening exercises 2 or more days a week. Although no SB recommendations were made in this document it was highlighted as a future research area that would subsequently shape future global PA guidelines (World Health Organization., 2010).

In 2011, Canada created the world's first SB specific guidelines named the *Canadian Sedentary Behaviour Guidelines for Children and Youth*, advising youth (12–17 years) minimise time spent sedentary by participating in no more than 2 hours per day of recreational screen time and limiting sedentary transport, prolonged sitting and time indoors (Tremblay, Leblanc, Janssen, et al., 2011). In the same year, the first UK PA Guidelines were published (*Start Active, Stay Active: UK Physical Activity Guidelines*), recommending children and young people (5–18 years) engage in at least 60 minutes MVPA and up to several hours every day incorporating VPA including those that strengthen muscle and bone at least 3 times a week. For adults (19–64 years), at least 150 minutes of moderate PA (MPA) in at least 10-minute bouts or 75 minutes of VPA per week was recommended, or a combination of MPA and VPA. Additionally, muscle strengthening activities 2 times per week were recommended. Prolonged sitting was advised to be minimised for both age groups (UK Chief Medical Officers, 2011).

The first age specific sleep duration guidelines were then published in 2015, named *The National Sleep Foundation Sleep Duration Recommendations* advising adolescents (14–17 years) achieve 8–10 hours and adults achieve (26–64 years) 7–9 hours of sleep each day (Hirshkowitz et al., 2015). Following this guideline, consensus statements by The American Academy of Sleep Medicine and Sleep Research Society produced similar sleep duration recommendations for adolescents (13–18 years; 8–10 hours per 24-h) and adults (18–60 years; 7+ hours per 24-h) (Paruthi et al., 2016; Watson et al., 2015).

Then, in 2016, Canada once again advanced movement behaviour guideline development by creating the first 24-h MB guidelines named *The Canadian 24-hour Movement Guidelines for Children and Youth.* These guidelines acknowledge the small percentage MVPA accounts for within the 24-hour day (<5%), *move* away from the previous dominant focus on MVPA and additionally considers the percentage of sleep (40%), SB (40%) and light PA (LPA; 15%) (Chaput, Carson, Gray, & Tremblay, 2014). The guidelines recommend youth (14–17 years) accumulate at least 60 minutes of MVPA per day comprised of a variety of aerobic activities, incorporating

VPA, muscle and bone strengthening activities at least 3 times per week and several hours of LPA per day. Additionally, recreational screen time should be limited to 2 hours per day and prolonged sitting reduced. Finally, a sleep duration of 8–10 hours per night with consistent bed and wake times are recommended. Supplementary information advised greater health benefits will be achieved through the preservation of sleep, substituting indoor with outdoor activity and replacing SB and LPA with MVPA (Tremblay et al., 2016). This 24-hour guideline approach was quickly adopted by several other countries and globally (New Zealand, Australia, South Africa, Finland, Croatia, WHO). The 24-hour guidelines specific to youth include, New Zealand's *Sit Less, Move More, Sleep Well: Physical Activity Guidelines for Children and Young People (5–17 years)* published *i*n 2017 and the *Australian 24-hour Movement Guidelines for Children (5–12 years) and Young People (13–17 years)* published in 2018. Each outline the same recommendations as the Canadian 24-hour guidelines for children and youth (New Zealand Ministry of Health, 2017; Okely et al., 2019).

The most recent UK movement guidelines (*The UK Chief Medical Officers' Physical Activity Guidelines*) were released in 2019 and did not adopt a 24-hour approach. Instead, the guidelines recommend children and young people (5–18 years) participate in at least 60 minutes of MVPA per day throughout the week of various types to develop movement skills, muscular fitness and bone strength and highlighted the context in which this could be achieved (physical education, active travel, after-school activities, play and sports). For adults (19–64 years), at least 150 minutes of MPA or at least 75 minutes of VPA or shorter durations of very vigorous PA (VVPA) or a combination of all intensities a week. Additionally, muscle strengthening activities should be incorporated at least 2 times per week.

Additionally, for both children/young people and adults, a reduction in SB and breaking up inactivity with at least LPA are recommended (UK Chief Medical Officers, 2019).

In 2020, Canada released the first adult 24-hour guideline named the *Canadian 24-hour Movement Guidelines for Adults.* These guidelines recommend adults (18–64 years), participate in a variety of types and intensities of PA throughout the 24-hour day resulting in the accumulation of at least 150 minutes of aerobic MVPA per week and muscle strengthening activities at least 2 times per week. Additionally, several hours of LPA per day is recommended. For SB, no more than 8 hours of sedentary time should be accumulated each day which includes, no more than 3 hours of recreational screen time and breaking up periods of prolonged sitting. For sleep, 7–9 hours of regular, good-quality sleep with consistent bed and wake times are recommended. Additionally, greater health benefits are obtained when sufficient sleep is preserved, SB is replaced with PA and LPA is replaced by MVPA (Ross et al., 2020).

Finally, the most recent global movement behaviour guidelines released in 2020 (*WHO Guidelines on Physical Activity & Sedentary Behaviour*) did not adopt a 24-hour approach, instead, focus was placed on PA and SB and that any PA is better than none. For children and adolescents (5–17 years), at least an average of 60 minutes a day of mostly aerobic MVPA throughout the week incorporating aerobic VPA, including muscle and bone strengthening activities at least 3 days a week were recommended. Additionally, SB should be limited, particularly recreational screen time. For adults (18–64 years), at least 150–300 minutes moderate or at least 75–150 minutes of vigorous aerobic PA or an equivalent combination of MPA and VPA throughout the week and muscle strengthening activities of moderate or greater intensity 2 or more times per week are recommended. For additional health benefits MPA of greater than 300 minutes of MPA and 150 minutes of VPA a week or an equivalent combination of each are recommended. Finally, SB should be reduced and replaced by any intensity of PA and achieving the MVPA recommendations reduces the detrimental effects of SB (Bull et al., 2020).

Although the WHO did not adopt a 24-hour approach for these age groups, key underlying principles of the 24-H MB and health paradigm were highlighted in the guideline summary. For example, the summary highlights SBs detrimental effect on sleep duration, PAs positive influence on sleep and the importance of replacing SB with PA (Bull et al., 2020). The 2020 *Canadian 24-hour Movement Guidelines for Adults* and *the WHO Guidelines on Physical Activity & Sedentary Behaviour* have been produced using the same evidence base. The different recommendations largely reflect the way in which lower quality evidence has been considered by different guideline development panels, in that, Canada has considered evidence of lesser quality and the WHO have not (Tremblay & Ross, 2020). However, recommendations based on low quality evidence are superior to the complete absence of recommendations, providing the advantages of such outweigh potential disadvantages. Imperfect evidence need not be discarded. Moreover, providing guidelines on multiple movement behaviours increases the number of opportunities to promote health (Tremblay & Ross, 2020).

5. 24-hour movement behaviours in adolescents with type 1 diabetes

Despite the well documented health benefits of PA, SB and sleep on health outcomes, there is a notable gap in research on 24-h MB in adolescents living with

T1D. A study conducted by Elmesmari, Reilly, and Paton (2022) compared 24-h MB levels of children with chronic conditions, including those with T1D, to children without a chronic condition and reported children with chronic conditions had a lower step count, higher sedentary time and greater sleep disruptions.

Until very recently, no studies had directly investigated 24-h MBs in adolescents living with T1D. However, a study published in July 2025 by Muñoz-Pardeza et al. (2025) addressed this gap, drawing on the rationale established by the present thesis's systematic review (see Chapter 2) (Patience et al., 2023). Muñoz-Pardeza et al. (2025) aimed to investigate the association of 24-h MB with HbA1c and interstitial glucose in children and adolescents living with T1D using 24-h compositional analysis. They reported that a higher daily amount of SB, at the expense of sleep time, LPA or MVPA, was positively associated with HbA1c and interstitial glucose, while more sleep time, at the expense of SB, LPA or MVPA, was associated with a significant reduction in HbA1c. Furthermore, reductions in both interstitial glucose were observed with increased daily time spent in MVPA at the expense of SB.

These aforementioned studies highlight the relevance of 24-h MBs in the management of T1D for adolescents and should be promoted with equal importance in the context of the entire day. A holistic 24-h MB approach that considers all behaviours in relation to one another would be appropriate as it would allow adolescents and clinicians to obtain the full picture of T1D management requirements and inform health interventions tailored to this group. Although 24-h MBs emphasise the integration of PA, SB and sleep, existing recommendations and research tend to address these behaviours individually. Therefore, the following sections review the current recommendations and research for each behaviour separately to provide context for how they may collectively contribute to optimum health and management.

5.1 Physical activity

The International Society for Paediatric and Adolescent Diabetes (ISPAD) and The American Diabetes Association (ADA) recommend adolescents with T1D should engage in at least 60 minutes of moderate to vigorous physical activity (MVPA) daily which aligns with general health recommendations for children and adolescents (Adolfsson et al., 2018; Colberg et al., 2016). However, many adolescents with T1D do not meet these guidelines and may be less physically active than their non-diabetic peers (de Lima et al., 2017; Quirk, Blake, Tennyson, Randell, & Glazebrook, 2014). There are a number of factors that need to be considered for adolescents with T1D when they participate in PA that their non-diabetic counterparts may not need to consider. As previously mentioned in the *Movement Behaviour Definition* section, there are many subcategories of PA (e.g., exercise) and can vary depending on context and domain (e.g., occupational and leisure). Insulin and carbohydrate intake need to be considered before, during and after PA and the requirements of each will depend on the frequency, intensity, time/duration and type of exercise as these impact blood glucose in a variety of ways. This makes exercising with T1D challenging to manage and increases the number of perceived barriers of participating in PA (e.g., fear of hypoglycaemia, family and peer support, insufficient education) (Dash, Goyder, & Quirk, 2020).

Generally, higher intensity and anaerobic activities (i.e., like weightlifting and sprinting) result in higher blood glucose levels and potential hyperglycaemia. This is particularly pertinent if the exercise is completed early in the day with little or no prandial insulin (Guelfi, Jones, & Fournier, 2007). The rise of glucose is further intensified if exercise produces higher levels of the stress hormone (i.e., in a competitive environment). Therefore, in the case of anaerobic and higher intensity exercise insulin dose reductions are not recommended whereas post exercise insulin maybe required in the event of hyperglycaemia (Riddell et al., 2017). Conversely, lower intensity and aerobic activities (i.e., brisk walking or running) result in lower blood glucose and potential hypoglycaemia. To mitigate potential low blood glucose when participating in PA, a reduction of prandial insulin is recommended at the meal before exercise. Alternatively, a reduction in basal insulin is recommended. Even when these measures have been taken, increased carbohydrate intake might be required to prevent hypoglycaemia (Riddell et al., 2017). Mixed/interval aerobic and anaerobic activities (i.e., football or rugby) which are characterised by bouts of intense exercise interspersed with more moderate activity or rest result in a slower rate of fall in glycemia both during and after the exercise. Therefore, may not require insulin adjustments.

Although challenging to manage, there are many benefits of PA for adolescents living with T1Ds. As well as the established physical and mental health benefits associated with PA, studies have consistently reported PA influence in lowering HbA1c levels by approximately 0.3%–0.5% depending on baseline HbA1c levels, which ultimately results in a lower prevalence of diabetes related co-morbidities (e.g., retinopathy, neuropathy, etc) (Beraki, Magnuson, Sarnblad, Aman, & Samuelsson, 2014; Quirk et al., 2014). However, it is important to recognise that much of the evidence underpinning these associations is derived from observational studies with methodological limitations (e.g. heterogeneity in study design, reliance on self-reported PA and presence of confounding factors such as diet and insulin) resulting in limited causal inference (Quirk et al., 2014). The relationship between PA and glycaemic control is complex for individuals living with T1D and while PA may contribute to improvements in HbA1c there is a host of additional factors that influence this complex relationship. Furthermore, the direction of this relationship is unlikely to be unidirectional. While different forms and intensities of PA influence glycaemic responses, glucose levels before PA and hypoglycaemia/hyperglycaemia concerns may also influence engagement and glucose response to PA. This bidirectional interplay further complicates the interpretation of associations between PA and glycaemic outcomes in adolescents living with T1D (Aljawarneh et al., 2023).

Therefore, structured person-centred support to exercise consultations have been developed that consider the host of factors associated with individuals participating in PA in clinical settings. These emphasise the importance of individualised factors by ensuring they are at the core of the exercise consultation discussion. Once factors concerning the individual have been determined, duration, type and intensity of exercise will be considered alongside basal and bolus insulin conditions. The final stage of this exercise consultation involves consideration of planned and unplanned exercise alongside consideration of previous days exercise (Adolfsson et al., 2022).

5.2 Sedentary behaviour

There are currently no specific recommendations for SB in adolescents with T1D. Instead, SB is secondary to PA with the ISPAD exercise recommendations simply stating that adolescents should limit their SB time with a focus on recreational screen time (Adolfsson et al., 2018). Similarly, the ADAs exercise recommendations suggest adolescents living with T1D should limit SB as much as possible and to break up long periods of SB every 30 minutes (American Diabetes Association, 2021). However, a recent systematic review and meta-analysis of differences in SB adolescents with T1D and their peers living without diabetes highlighted adolescents with T1D's obtained 63.3 minutes more per day of SB (total sedentary time and screen time) than their non-diabetic peers (Huerta-Uribe, Hormazábal-Aguayo, Izquierdo, & Garcia-Hermoso, 2023). Additionally, Huerta-Uribe et al. (2023) conducted a systematic review and meta-analysis to determine the association between SB (total sedentary time and screen time) and HbA1c. They reported a positive association ($r = 0.20$, 95% CI 0.04 to 0.35; $I^2 = 92.6\%$) in that as SB increased HbA1c increased. SB levels also have implications for T1D specific psychosocial outcomes. Tilden, Noser, and Jaser (2023) examined the effect of SB on psychosocial outcomes (i.e., depressive symptoms, diabetes distress and quality of life) in adolescents living with T1D. They reported an association between sedentary time and diabetes distress in adjusted analysis for sex, age, race and baseline HbA1c (6.3; 95% CI: 1.3–11.2). The short-term effects of SB are less intense than PA in that severe glucose excursions occur less rapidly (Cuenca-Garcia, Jago, Shield, & Burren, 2012). Engaging in long periods of SB is often associated with hyperglycaemia and breaking up long bouts of SB by standing or LPA often mitigates the likelihood of hyperglycaemia occurring highlighting the importance of balancing both PA and SB (MacMillan et al., 2014). Considering the current evidence highlighting the relationship between higher SB levels and poorer diabetes specific physical and mental health outcomes, it would be pertinent to have greater emphasis on specific SB recommendation for adolescents living with T1D.

However, it is important to note that the aforementioned studies are correlational and are at risk of being skewed by potential confounding and mediating factors. SB is often coupled with other behaviours (e.g., eating/snacking) (Tremblay, LeBlanc, Kho, et al., 2011). Therefore, the multitasking nature of SB makes it difficult to ascertain the cause and effect of glucose variability when researching this behaviour. For example, adolescents might be watching TV or playing video games while simultaneously eating and any glucose variability might be attributed to the latter. Additionally, the activity completed while participating in SB can influence the behaviours relationship with glucose control. For example, studies investigating the relationship between homework activities are associated with better controlled HbA1c as the conscientiousness personality trait that facilitates homework completion also facilitates better T1D self-management (Rassart et al., 2018).

5.3 Sleep

While sleep research in diabetes has previously focused on adults with T2D (Knutson, Van Cauter, Zee, Liu, & Lauderdale, 2011; Ohkuma et al., 2013) resulting in established clinical screening recommendations (Schipper et al., 2021) similar guidance is lacking for adolescents with T1D (Davies et al., 2022; Henson et al., 2024). This gap is concerning given the known developmental and psychosocial challenges that contribute to poor sleep in adolescents (Carskadon, 2011; Crowley, Wolfson, Tarokh, & Carskadon, 2018) and the additional demands of managing T1D throughout the whole day.

Adolescents with T1D are expected to follow general sleep recommendations of 8–10 hours per night (Paruthi et al., 2016; Watson et al., 2015), but studies consistently show they fall short, with reported durations ranging from 6.5–7.7 hours (Frye, Perfect, & Silva, 2019; Jaser & Ellis, 2016; Patel et al., 2018; Rechenberg et al., 2020; von Schnurbein et al., 2018). Even when they meet recommendations, it's often at the lower end (McDonough, Clements, DeLurgio, & Patton, 2017; Perfect, 2014).

There is a strong degree of evidence suggesting adolescents with T1D obtain significantly less sleep than peers without T1D (de Lima et al., 2017; Reutrakul et al., 2016; Rose et al., 2021). However, some contradictory evidence suggests T1D adolescents sleep longer than peers (Hazen et al., 2015; Yeshayahu & Mahmud, 2010) and another study reported no significant differences between groups (Macaulay et al., 2020).

The relationship between sleep duration and glycaemic control (HbA1c) remains inconsistent. Longer sleep has been linked to both better (Macaulay et al., 2020; Perfect, 2014; Silva et al., 2021) and worse HbA1c (Hazen et al., 2015), or no association at all (McDonough et al., 2017; Reutrakul et al., 2016). Subjective sleep quality is also frequently reported as poor among T1D adolescents with no significant associations observed with HbA1c (Hamburger, Goethals, Choudhary, & Jaser, 2020; Jaser & Ellis, 2016; Patel et al., 2018; Perfect et al., 2012; Rose et al., 2021). Interventional research in this area is emerging. A sleep extension trial by Perfect, Frye, and Bluez (2018) showed improved glucose control and increased time in range among adolescents with T1D. However, a pilot sleep coaching study did not observe significant HbA1c changes despite gains in sleep efficiency and duration (Jaser et al., 2020). Additional trials are underway however, more interventional evidence is required (Perfect et al., 2023; Rose et al., 2021). Consistent with patterns observed for PA, the relationship between sleep and glycaemic control in adolescents living with T1D is increasingly conceptualised as bidirectional rather than linear. Glycaemic variability can disrupt sleep (e.g. nocturnal hypoglycaemia/hyperglycemia and diabetes technology related awakenings), which may contribute to the inconsistent associations reported between sleep and HbA1c within the literature (Jaser et al., 2016; Perfect et al., 2014). This underscores the difficulty of inferring directionality from predominantly cross-sectional evidence.

6. Thesis aims and structure

The overall aim of this thesis was to explore the feasibility of a 24-h MB approach in adolescents living with T1D. The findings of this thesis will allow for a more holistic understanding and approach to T1D management in adolescents. **Chapter 1** of this thesis provides an introduction into the key research areas (i.e., T1D, adolescents, and 24-h MBs). This chapter provides greater insight into important rationales made for the first study produced for this thesis, a systematic review and meta-analysis. The purpose of **Chapter 2** (first study) was to identify gaps in the current literature on 24-h MB and T1D and understand how these movement behaviours impacted important T1D outcomes in adolescents with T1D. This chapter has been published in the International Journal of Environmental Research and Public Health (Patience et al., 2023) and has since been cited in and used to inform the American Diabetes Association Standards of Care in Diabetes for 2023–2025 (American Diabetes Association., 2025).

Chapter 3 discusses the data collection methods utilised for the second and third study and discusses important data collection considerations (i.e., practical and moral boundaries) and best practice associated with conducting research in adolescents with T1D and similar groups living with chronic conditions. The purpose of **Chapter 4** (second study) was to conduct a micro-longitudinal study measuring 24-h MB levels in adolescents living with T1D using wrist-worn accelerometery. HbA1c and quality of life was also captured, and an exploratory analysis was conducted to indicate relationships between the variables. This chapter is currently being prepared for submission.

Chapter 5 (third study) aimed to understand the perceptions adolescents with T1D have toward a 24-h MB approach and explored how they might believe each behaviour to interact with one another and how they believed these behaviours impacted important T1D outcomes. This chapter has been published in the International Journal of Environmental Research and Public Health (Patience, Kirk, Janssen, Sanders, & Crawford, 2025). The thesis concludes with **Chapter 6** where a summary of findings is presented alongside a discussion surrounding how these findings can inform future research and clinical practice.

Chapters 2, 4 and 5 contains a preface that introduces each study and outlines the rationale and background for each study to position the research. Additionally, the preface will include details about each studies preparation and specific methodologies. Following the preface, the aforementioned chapters present the corresponding articles and manuscript prepared for publication, formatted in accordance with the target journal's guidelines.

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Chapter 2 - Study One, Systematic Review and Meta-Analysis of 24-h Movement Behaviours

1. Chapter Overview

This aim of this chapter is to present the first study of the PhD, a systematic review and meta-analysis examining 24-h MBs relationship with key health outcomes in adolescents with T1D. A pre-planning phase identified gaps in existing literature, which largely examined these behaviours in isolation and lacked integration of both quantitative and qualitative evidence. In response, a mixed methods systematic review was conducted following PRISMA guidelines. This included a comprehensive literature search, quality appraisal, data extraction and data synthesis. The findings addressed a critical evidence gap and contributed to informing international guidelines. The full study has been published in the *International Journal of Environmental Research and Public Health* and has since informed the 2025 *American Diabetes Association Standards of Care* (DOI: https://doi.org/10.2337/dc25-S005).

2. Pre-planning phase and gap identification

Prior to conducting the systematic review and meta-analysis, it was important to firstly identify the current systematic reviews available in relation to 24-h MBs and adolescents with T1D. A preliminary literature search was conducted in 2020, including a search of any registered protocols within the international systematic review registry, PROSPERO. Seven relevant systematic reviews were identified, though most focused-on movement behaviours in isolation, and primarily on PA. No existing reviews adopted an integrated 24-h MB framework, nor did they combine quantitative and qualitative evidence. These gaps highlighted the need for a systematic review synthesising both qualitative and quantitative studies investigating all three of the movement behaviours within a 24-h MB paradigm and their broader implications for adolescents living with T1D. Following the identification of these gaps, a research question was formulated, and the proposed systematic review was registered in PROSPERO (CRD42021232460). Throughout planning, conducting and reporting of this systematic review the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was utilised to allow users to assess the trustworthiness and applicability of review findings (Page et al., 2021).

Table 2.1: Identified systematic reviews in the pre-planning and gap identification phase.

Author & Date	Title	Movement Behaviour Investigated	Quantitative, Qualitative or Mixed
(Quirk, Blake, Tennyson, Randell, & Glazebrook, 2014)	Physical activity interventions in children and young people with Type 1 diabetes mellitus: a systematic review with meta-analysis (RCTs & Non-RCTs)	PA	Quantitative

(MacMillan et al., 2014)	A systematic review of physical activity and sedentary behavior intervention studies in youth with type 1 diabetes: study characteristics, intervention design and efficacy (RCTs)	PA & SB	Quantitative
(Lukacs & Barkai, 2015)	Effect of aerobic and anaerobic exercises on glycemic control in type 1 diabetic youths (RCTs)	PA	Quantitative
(Absil, Baudet, Robert, & Lysy, 2019)	Benefits of physical activity in children and adolescents with type 1 diabetes: A systematic review (RCTs)	PA	Quantitative

(Aljawarneh, Wardell, Wood, & Rozmus, 2019)	A Systematic Review of Physical Activity and Exercise on Physiological and Biochemical Outcomes in Children and Adolescents With Type 1 Diabetes (Interventional & Observational)	PA	Quantitative
(Dash, Goyder, & Quirk, 2020)	A qualitative synthesis of the perceived factors that affect participation in physical activity among children and adolescents with type 1 diabetes	PA	Qualitative
(Perfect, 2020)	Sleep-related disorders in patients with type 1 diabetes mellitus: current insights	Sleep	Quantitative

3. Systematic review stages

Once research gaps have been identified and research questions have been developed, subsequent stages of the systematic review process must be adhered to (Davis, 2016; Zaccagnini & Li, 2023). A comprehensive search of the literature should take place that specifies the types of information sources and specific resources that will be searched (e.g., bibliographic databases, grey literature, particular databases), your search terms, how you will include and exclude papers (e.g., inclusion and exclusion criteria, use of screening and referencing software's) and how you will report the results of your search (e.g. PRISMA flow diagram of included studies). Additional information surrounding the exact definition of search terms and the full search strategy is discussed in detail in **Appendix C** and **Appendix D**, respectively.

Once the literature search has been conducted and researchers have the final articles that meet inclusion criteria, these must go through quality appraisal. Quality appraisal is an advanced form of evaluation which encourages the researcher to evaluate the included literature in a structured way by considering the design of the study, validity of findings, likelihood of bias and the relevance of findings in relation to similar research. There are several quality appraisal tools available (e.g., CASP, STROBE, PRISMA, GRADE) and the selection of the tool depends on the research being conducted. Quality appraisal data for this study was collated using a Microsoft Excel sheet due to the high volume of studies and can be found in **Appendix G**.

Following critical appraisal of included studies, researchers can begin to extract data. The exact information researchers choose to extract depends on their research however, reviewing similar research in the field is often useful. Data extraction for this systematic review was collated using a Microsoft Excel sheet.

Once data has been extracted, information can be presented either narratively (e.g., study type, number and characteristics of participants, comparators and outcomes) or statistically (e.g., meta-analysis) providing there are a good number of studies and that are not too homogeneous (Hansen, Steinmetz, & Block, 2022). In this systematic review data was presented narratively and statistically using a meta-analysis. A forest plot of all PA and SB individual studies can be found in **Appendix A** and **Appendix B**. The narrative synthesis of both quantitative and qualitative studies included for this systematic review can be found in **Appendix H** and **Appendix I**. Each of these aforementioned systematic review stages are discussed fully within the main manuscript.

4. Study one: 24-hour movement behaviours (physical activity sedentary behaviour and sleep) association with glycaemic control and psychosocial outcomes in adolescents with type 1 diabetes: a systematic review of quantitative and qualitative studies

International Journal of
Environmental Research and Public Health

Systematic Review

24-Hour Movement Behaviours (Physical Activity, Sedentary Behaviour and Sleep) Association with Glycaemic Control and Psychosocial Outcomes in Adolescents with Type 1 Diabetes: A Systematic Review of Quantitative and Qualitative Studies

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Abstract: Type 1 Diabetes (T1D) is a condition requiring 24-hour management. The way in which an individual combines their 24-hour movement behaviours (24-h MBs), which is comprised of physical activity (PA), sedentary behaviour (SB), and sleep, throughout the day can have a significant impact on physical and mental health. This mixed methods systematic review aimed to investigate 24-h MBs' relationship with glycaemic control and psychosocial outcomes in adolescents (11–18 years) with T1D. Ten databases were searched for quantitative and qualitative English language articles reporting at least one of the behaviours and their relationship with outcomes. There were no restrictions on article publication dates or study design. Articles were subjected to title and abstract screening, full text screening, data extraction and quality assessment. Data were summarised narratively, and a meta-analysis was conducted where possible. From 9922 studies, 84 were included for data extraction (quantitative (n = 76), qualitative (n = 8)). Meta-analyses revealed a significant favourable association between PA and HbA1c (−0.22 [95% CI: −0.35, −0.08; I^2 = 92.7%; p = 0.001). SB had an insignificant unfavourable association with HbA1c (0.12 [95% CI: −0.06, 0.28; I^2 = 86.1%; p = 0.07]) and sleep had an insignificant favourable association (−0.03 [95% CI: −0.21, 0.15; I^2 = 65.9%; p = 0.34]). Importantly, no study investigated how combinations of behaviours collectively interacted and impacted on outcomes.

Keywords: 24-hour movement behaviours; physical activity; sedentary behaviour; sleep; type 1 diabetes; adolescents; glycaemic control; quality of life; review

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Citation: Patience, M.; Janssen, X.; Kirk, A.; McCrory, S.; Russell, E.; Hodgson, W.; Crawford, M. 24-Hour Movement Behaviours (Physical Activity, Sedentary Behaviour and Sleep) Association with Glycaemic Control and Psychosocial Outcomes in Adolescents with Type 1 Diabetes: A Systematic Review of Quantitative and Qualitative Studies. *Int. J. Environ. Res. Public Health* **2023**, *20*, 4363. https://doi.org/10.3390/ijerph20054363

Academic Editor: Paul B. Tchounwou

Received: 8 December 2022
Revised: 21 February 2023
Accepted: 22 February 2023
Published: 28 February 2023

1. Introduction

Type 1 Diabetes (T1D) is a condition characterised by insulin deficiency, resulting in blood glucose levels having to be monitored and managed over the full 24-hour day using complex patterns of insulin administration. Everyday activities can affect blood glucose levels and management decisions are constantly required to maintain stable glycemia [1,2]. Although T1D can develop at any age, it most commonly develops during childhood and adolescence and is the most common form of diabetes for these age groups. The global estimate for children and adolescents (<20 years old) diagnosed with the condition is 1,211,900 with an estimated 149,500 diagnosed each year [3].

Adolescence is recognised as a particularly challenging time for individuals with T1D due to increased ownership of their condition and navigation of the usual changes occurring throughout adolescence (e.g., changes to the social environment, exploration of different lifestyles, biological changes, academic/work pressures etc.) [4]. The deterioration of metabolic control in T1D commonly occurs during adolescence with 13–25-year-olds experiencing the worst average plasma glucose concentration (HbA1c compared to other age groups) [5]. A range of mental health issues can also occur during this period, including depression and anxiety, impacting individuals' psychosocial functioning [6,7].

Previous systematic reviews and research examining 24-hour movement behaviours (physical activity (PA), sedentary behaviour (SB), and sleep) and their relation to physical and mental health outcomes in adolescents with T1D have investigated these behaviours in isolation, with greatest emphasis placed on PA [8]. However, there has been a recent paradigm shift in the movement science literature suggesting individual movement behaviours for health should no longer be examined in isolation [9]. Instead, an integrated approach should be adopted, where all movement behaviours within the 24-hour day exist as a continuum from no movement (e.g., sleep) through low movement (e.g., sedentary behaviour) to high movement (e.g., vigorous PA (VPA)). These behaviours are considered relative or time-dependent, which means a decrease in one behaviour will result in a change in one of the other behaviours. Importantly, the way in which an individual combines these movement behaviours throughout the day can have a significant impact on physical and mental health [10].

In addition to the lack of systematic reviews investigating movement behaviours in youth with T1D in relation to the whole 24-hour day, there is a lack of systematic reviews examining quantitative and qualitative movement behaviour data together and their impact on T1D mental and physical health outcomes in adolescents. This would provide a comprehensive synthesis of the evidence beyond what is currently offered by a single method review by bringing together the findings of effectiveness (quantitative evidence) and experience (qualitative evidence) to enhance their usefulness to decision makers. Therefore, the aim of this study is to conduct a systematic review of quantitative and qualitative studies to comprehensively investigate 24-hour movement behaviours (individual and/or combined) and their impact on primary (glycated haemoglobin (HbA1c) and continuous glucose monitoring (CGM) metrics and quality of life (QoL)), and secondary outcomes (depressive symptoms, anxiety, stress/distress, self-management, coping, diabetes self-efficacy, family functioning, social competence) in adolescents with T1D.

2. Methods

2.1. Scientific Rigor

The protocol for this systematic review was registered on the 24 March 2021 in PROSPERO, the international prospective register of systematic reviews (CRD42021232460). The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was used within the planning, conducting, and reporting of this review [11].

2.2. Inclusion Criteria

The inclusion criteria for the quantitative and qualitative studies (Table 1) were informed by PICOS (Population, Intervention, Comparison Group, Outcome, Study Design) and SPIDER (Sample, Phenomena of Interest, Design, Evaluation, Research Type) eligibility criteria, respectively [12,13].

Table 1. Eligibility criteria for the quantitative and qualitative studies.

PICOS Statement (Quantitative)	SPIDER Statement (Qualitative)
Population: Adolescents (11–18 years) with researcher defined diagnosed type 1 diabetes	Sample: Adolescents (11–18 years) with researcher defined diagnosed type 1 diabetes and primary caregivers/parents of adolescents with researcher defined diagnosed type 1 diabetes
Intervention/Exposure: Individual or combined 24-hour movement behaviours	Phenomenon of Interest: At least one 24-hour movement behaviour theme
Comparisons: All control/comparison groups	Design: All qualitative methods
Outcomes: HbA1c, CGM metrics and QoL	Evaluation: Beliefs, experiences, attitudes, behaviours and interactions etc.
Study: Interventional/experimental and observational	Research Type: Qualitative

HbA1c, haemoglobin A1c; CGM, continuous glucose monitor; QoL, quality of life.

2.3. Population/Sample

Adolescents aged 11–18 years with investigator-defined T1D of all genders, all ethnicities and all diabetes durations were included. For the qualitative studies, the primary caregivers/parents of the adolescents with diagnosed T1D were also included providing their perspectives related specifically to the adolescent.

2.4. Intervention/Exposure and Phenomenon of Interest

Any individual or combined 24-hour movement behaviours (PA, SB and sleep) were included for this systematic review. Studies were included provided they were investigating habitual/usual PA. All subcategories of SB were considered (e.g., overall sedentary time, screen time and non-screen time behaviours). For sleep, all dimensions related to sleep health were included (e.g., duration, continuity or efficiency, timing, alertness/sleepiness and satisfaction/quality) [14] (Supplementary Materials Glossary of Terms S1). All outcomes of movement behaviours and related subcategories (e.g., cardiorespiratory, metabolic, muscular, morphological or motor physical fitness) were excluded.

2.5. Comparisons and Design

For the quantitative studies, all control/comparison groups were included in this review provided they were within the identified population age bracket. For the qualitative studies, all qualitative methods were considered. Only data collected in habitual settings were gathered (e.g., sleep measured within a sleep lab and physical activity measured during an exercise test within a lab were excluded unless habitual movement behaviours were also reported).

2.6. Outcomes and Evaluation

The primary outcomes of interest for the studies were glycaemic control measured by HbA1c and/or standardised CGM metrics and QoL [15,16]. Tests/measures of QoL, Health Related Quality of Life (HRQoL) and Diabetes Specific Quality of Life providing global/total scores were reported. The secondary outcomes of interest were psychosocial (individual and family level) responses [17]. Psychosocial responses were defined as depressive symptoms, anxiety, stress/distress, self-management, coping, self-efficacy, family functioning and social competence [18] (Supplementary Materials Glossary of Terms S1). For the qualitative studies, a range of phenomena were under investigation (for example, views, behaviours, opinions, attitudes, perceptions, experiences and beliefs).

2.7. Study and Research Type

This systematic review collected quantitative, qualitative, and mixed method studies. Mixed method studies were only considered if data from the quantitative or qualitative components could be clearly extracted. Specifically, quantitative included experimental/interventional studies (e.g., randomised, and non-randomised) and any non-experimental/observational studies (e.g., cross-sectional/prevalence, cohort/longitudinal, case control/case reference). Additionally, all qualitative studies were included (e.g., ethnography, phenomenology, grounded theory, narrative inquiry, case studies and visual and participatory methodologies). All commentaries, reviews, editorials, meta-analysis, and diagnostic studies were excluded from this review.

2.8. Search Strategy

An electronic literature search was conducted on the 7th of May 2021 in the following electronic databases: MEDLINE (Ovid), EMBASE (Ovid), Web of Science (Core Collection), APAPsychINFO (EBSCOhost), SPORTDiscus (EBSCOhost), Applied Social Sciences Index and Abstracts (ProQuest), Sports Medicine and Education Index (ProQuest) Wiley Cochrane Library, OpenGrey and Open Dissertations (EBSCOhost). All published studies up until the search date were included provided they met the inclusion criteria. For each database, a search strategy consisting of keywords and synonyms was developed using the PICO and SPIDER frameworks (Supplementary Materials Search Strategy S2).

2.9. Screening Process

All identified citations (n = 9922) were initially compiled into EndNote reference management software (https://endnote.com (accessed on 15 May 2021)) to remove duplicates [19]. The remaining references (n = 6513) were exported to Covidence systematic review software (https://www.covidence.org (accessed on 15 May 2021)). Further duplicates identified by Covidence were removed [n = 14], resulting in a total of 6499 references for title and abstract screening.

Independent screening of the studies occurred at the title and abstract stage and the full text stage by four reviewers (M.P., S.M., E.R., W.H.). Authors were contacted for missing texts. The eligibility of each study was confirmed through completion of quantitative and qualitative inclusion/exclusion checklist. Any disagreements surrounding the exclusion or inclusion of studies at each stage were discussed until a unified decision was made. If a consensus could not be reached, a third reviewer was consulted (X.J.). Cohen's Kappa [κ] was calculated between each reviewer pair for the title and abstract (0.60–0.85) and full text screening stages (0.62–0.69) [20] (Supplementary Materials Table S1).

2.10. Data Extraction

The PICO (quantitative) and SPIDER (qualitative) criteria were used to inform data extraction. Sample characteristics (e.g., age, diabetes duration, HbA1c and sample size), study design (e.g., experimental, cross sectional, cohort and case-control), exposure/intervention description (e.g., movement behaviour and measurement method), primary and secondary outcomes and results data were extracted from studies (Supplementary Materials Table S2). Four reviewers completed independent data extraction for the quantitative studies (M.P., S.M., E.R., W.H.) and two reviewers completed independent extraction for the qualitative studies (M.P., S.M.). Any disagreements were discussed, and a third reviewer was consulted when a consensus could not be reached (X.J.).

2.11. Quality Assessment

The Critical Appraisal Skills Programme checklists were utilised to assess the methodological quality of the cohort, case-control, randomised control trials and qualitative studies [21]. The Strengthening of Reporting of Observational Studies in Epidemiology checklist was utilised for the included cross-sectional studies [22]. Assessment of each included study was performed by M.P. No studies were excluded based on quality assessment (Supplementary Materials Table S3).

2.12. Data Synthesis

2.12.1. Narrative Synthesis of Quantitative Studies

The Excel database utilised for quantitative data extraction was initially examined by movement behaviour and respective movement behaviour constructs (Supplementary Materials Table S2). Each movement behaviour was examined in relation to the primary and secondary outcomes of interest for favourable results, unfavourable results, or results with no significance. Results were deemed favourable if the outcomes improved or indicated a trend for improvement due to higher levels of the movement behaviour. For example, for correlational results, PA's negative correlation with HbA1c would be deemed favourable as higher PA reduced (improved) HbA1c. Additionally, for studies examining differences, results would be deemed favourable if groups with higher PA had lower (improved) HbA1c (Supplementary Materials Tables S4–S7).

2.12.2. Narrative Synthesis of Qualitative Studies

Findings/themes from each qualitative study were gathered and accompanied by illustrations (e.g., quote). Findings were then grouped by common movement behaviour categories. Textual pooling was not possible due to a low number of included qualitative studies that were also very heterogenous and were therefore presented in narrative form (Supplementary Materials Table S8).

2.12.3. Meta-Analysis Synthesis

Meta-analyses of quantitative studies were performed using the Meta-Essentials tool [https://www.erim.eur.nl/research-support/meta-essentials/ (accessed on 7 March 2022)]. The tool consists of a set of workbooks designed for Microsoft Excel that, based on the input, automatically produces all the required statistics, tables, figures, and more [23]. All the included studies for the meta-analysis included cross sectional associations between exposure and outcome which were derived from cross-sectional and longitudinal study designs only. For the longitudinal studies, the correlation statistic that was closest to the exposure was taken to highlight acute opposed to chronic effects of the exposure. Authors viewed this as more in keeping with associations present in cross-sectional studies. Correlation coefficients were extracted from studies and beta (b) coefficients were extracted and converted to correlation coefficients [24]. The I^2 statistic was utilised to determine heterogeneity between studies and subsequent random-effect or fixed effect analysis (0–40% = low heterogeneity; 75–100% = significant heterogeneity) [25].

Meta-analyses were possible between the following exposure-outcome associations and their subgroups (if applicable):

- PA and HbA1c (Subgroups = Light-PA (LPA), Moderate-PA (MPA), Vigorous-PA (VPA), Moderate-Vigorous-PA (MVPA) and Total-PA (TPA)).
- SB and HbA1c (Subgroups = Computer, TV, Total Screen Time, Schoolwork and Total Sedentary Time).
- Sleep and HbA1c (Duration dimension only due to study heterogeneity).

Unfavourable associations and favourable associations were determined based on the direction of association. For PA exposures, a negative association was deemed favourable (e.g., more PA associated with lower HbA1c) and a positive association was deemed unfavourable (e.g., more PA associated with higher HbA1c). For SB exposures, a positive association was deemed favourable (e.g., less screen time associated with lower HbA1c) and a negative association was deemed unfavourable (e.g., less screen time associated with higher HbA1c). For sleep duration, a negative association was deemed favourable (e.g., increased sleep duration was associated with lower HbA1c) and a positive association was deemed unfavourable (e.g., increased sleep duration was associated with higher HbA1c).

3. Results

3.1. Characteristics of Identified Studies

In total, 9922 articles were identified from the initial search with 84 articles included for data extraction after title, abstract and full text screening (quantitative (n = 76) [26–101] qualitative (n = 8) [102–109] (Figure 1). Included quantitative articles were published between 1990–2021 [26,53] and conducted in the USA (n = 28) [30,33,40–42,44–47,51,53,54,60,69,70,77,78,81–83,85–87,92,94,97], Europe (n = 25) [31,32,39,43,48–50,56–59,61–64,67,68,75,80,89–91,93,96,98] UK (n = 6) [34,37,38,66,72,88], South America) (n = 5) [35,36,71,74,84], Middle East (n = 4) [27,76,100,101], Canada (n = 3) [73,79,99], Africa (n = 2] [26,55], New Zealand (n = 1) [65] and across multiple countries (n = 2) [28,29]. There were two experimental [52,72], 10 case-control [26,36,39,57,61,63,65,82,97,99], 11 longitudinal [30,33,40,41,46,50,60,70,77,89,90] and 53 cross-sectional studies [27–29,31,32,34,35,37,38,42–45,47–49,51,53–56,58,59,62,64,66–69,71,73–76,78–81,83–88,91–96,98,100,101]. The sample of the quantitative studies included a total of 68,203 adolescents ranging from 10–23,251 [30,49] participants per study. The mean age of participants was 14.1 years (11.1–17.6 years) [54,66], with a mean diabetes duration of 5.8 years (0.5–12.5 years) and a mean HbA1c of 8.8% (73 mmol/mol) (7.2–10.2%) [47,50]. Included qualitative articles were published between 2009–2018 [102,103,105,108]. Six analysed data thematically [102,103,106–109], one used latent content analysis [105] and one used interpretive phenomenological analysis [104].

These studies were conducted in the UK (n = 5) [104,106–109], USA (n = 3) [102,103] and Europe (n = 1) [105]. The total adolescent sample of the qualitative studies was 105, ranging from 11–29 participants per study [105]. These adolescents had a mean age of 12.7 years (10.8–15.56 years) [102,109], a mean diabetes duration of 5.1 years [3.8–6.2 years] [102,106] and a mean HbA1c of 8.6% [8.3–8.9%] [102–104]. The total sample of parents was 92, ranging from 11–25 participants per study [102,108].

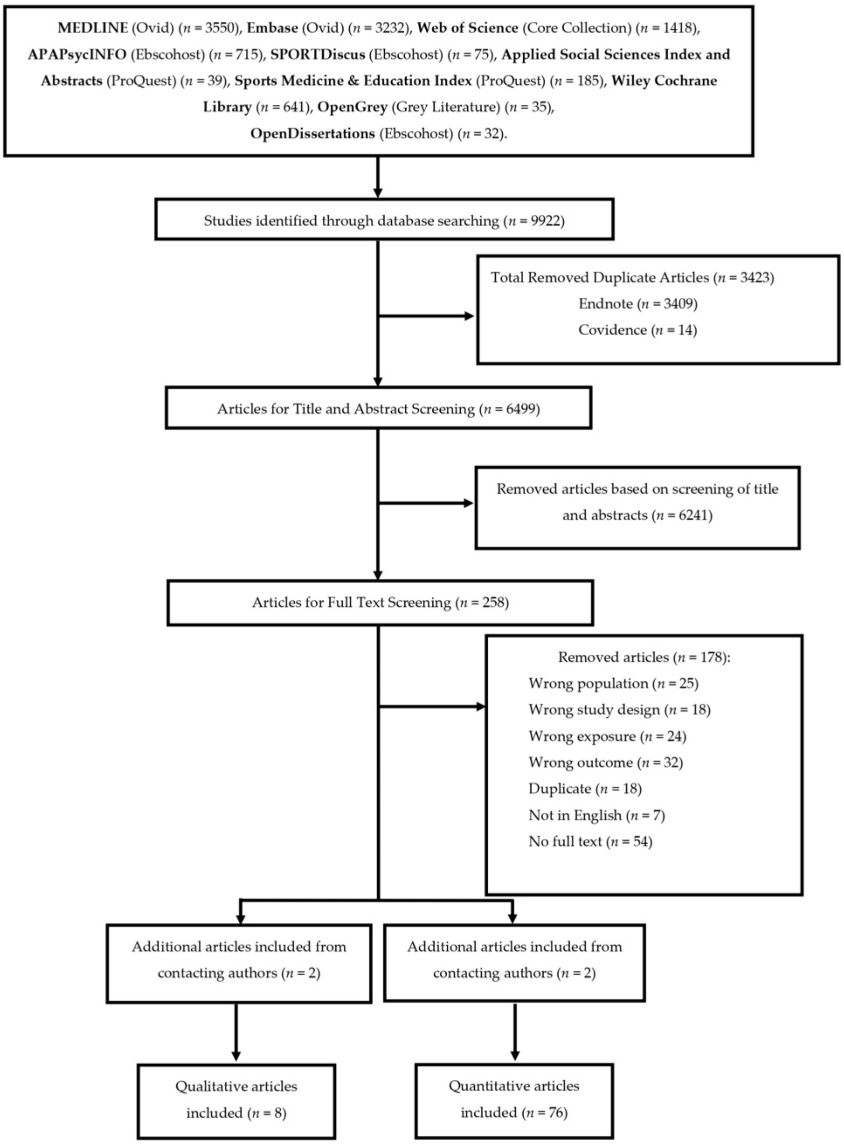

Figure 1. Flow chart of included studies.

3.2. Movement Behaviour Composition

Half of all the included quantitative and qualitative studies were investigating PA individually (n = 45; 53.57%) [27,29–32,34,35,37,38,40,41,48,49,53,55–57,59,61–64,68,74,76–78,80,84,86–89,91–94,96,104–109], 2.38% (n = 2) [60,67] of studies were investigating SB individually and 23.81% (n = 20) of studies were investigating sleep individually [26,42,44,45,47,51,52,65,69,81–83,85,95,97–99,101–103]. A total of 16.67% (n = 14) of studies were investigating both PA and SB [28,33,39,43,50,54,58,66,70,72,73,75,90,100], 1.19% (n = 1) [46] of studies were investigating both PA and sleep and 2.38% (n = 2) of studies were investigating all three behaviours [36,71] (Figure 2).

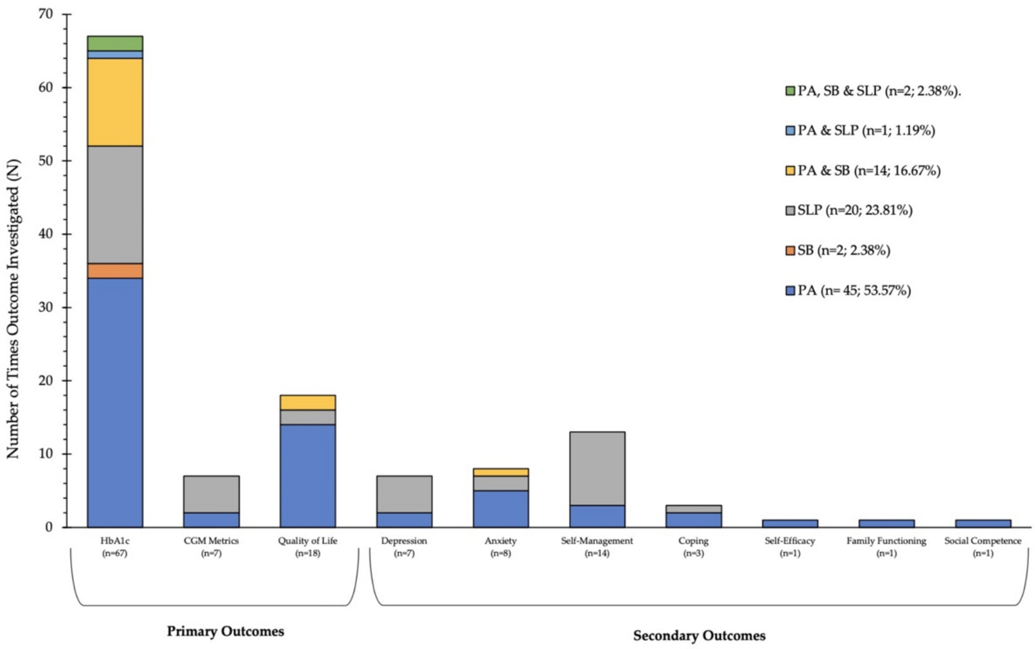

Figure 2. Movement Behaviours and the Addressed Primary and Secondary Outcomes of Included Studies. PA, physical activity; SB, sedentary behaviour; SLP, sleep; HbA1c, haemoglobin A1c; CGM, continuous glucose monitoring.

Specific physical activity constructs addressed in the included studies were TPA, MVPA, VPA, MPA and LPA. Sedentary behaviour constructs included total sedentary behaviour (SED), screen time (computer), screen time (television), sedentary behaviour (schoolwork) and screen time (TV and computer). Finally, sleep constructs addressed included duration, continuity/efficiency, timing, quality and alertness/sleepiness (Tables S4–S7).

3.3. Included Articles Primary and Secondary Outcome Composition

Examination of the primary outcomes showed HbA1c was addressed most frequently (n = 67), primarily by PA studies (n = 34) [27,30–32,34,37,38,40,41,48,49,53,55,56,61,63,64,68,74,76,78–80,86,88,89,92,94,96,104,106–109] followed by sleep (n = 16) [26,42,45,47,51,52,65,69,81–83,85,98,99,101,102] and then PA and SB studies (n = 12) [28,33,39,43,50,54,58,66,70,73,90,100]. QoL was the second most addressed outcome (n = 18), primarily by PA studies (n = 14) [29,30,35,41,55,62–64,76,77,93,104,106,107] followed by sleep (n = 2) [85,97] and PA and SB (n = 2) [72,75]. CGM metrics were the least frequently addressed primary outcome (*n* = 7), primarily addressed by sleep studies (*n* = 5) [44,47,65,82,85] followed by PA studies (*n* = 2) [84,91]. Examination of the secondary outcomes showed self-management was addressed most frequently (*n* = 13) [105], primarily by sleep studies (*n* = 10) [42,45,47,51,52,69,81,85,95,102]. Anxiety was the second most addressed (*n* = 8) [30,50,57,76,85–87,103] followed by depression (*n* = 7) [45,47,76,82,85,94,101]. The outcomes least frequently addressed were coping (*n* = 3) [85,93,109], self-efficacy (*n* = 1) [37], family functioning (*n* = 1) [106] and social competence (*n* = 1) [30] (Figure 2).

3.4. Physical Activity

Overall, PA's impact on HbA1c was favourable in 19/60 (32%) associations and unfavourable in 2/6 (3%), most results investigating PA and HbA1c were not significant (39/60) (60%). PA's impact on QoL was favourable in 11/15 (73%) associations, the remainder were not significant (20%). Overall, PA had no associations with depression, self-efficacy, family functioning and social competence. A mix of favourable and unfavourable associations with anxiety and self-management were observed with no clear pattern emerging (Tables S4–S7). The random effects meta-analysis to quantify associations between PA and HbA1c highlighted a significant negative association (overall pooled correlation coefficient = −0.22 [95% CI: −0.35, −0.08; I^2 = 92.7%, p = 0.001]. The subgroup analysis revealed negative associations with HbA1c for each PA construct (LPA = −0.48 [95% CI: −0.79, 0.03; I^2 = 17%]; MPA = −0.13 [95% CI: −0.48, 0.26; I^2 = 67.5%]; MVPA = −0.13 [95% CI: −0.29, 0.04; I^2 = 67%]; TPA = −0.18 [95% CI: −0.45, 0.12; I^2 = 95.1%] and VPA −0.22 [95% CI: −0.46, 0.04; I^2 = 73%]) (Figure 3). Please see Figure S1 for a forest plot of individual studies.

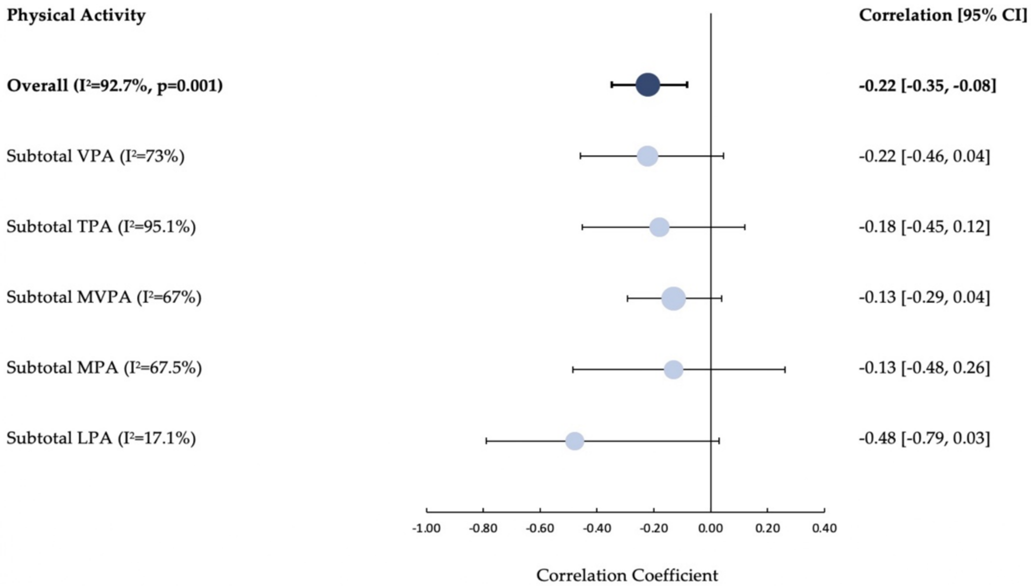

Figure 3. Forest Plot of the correlations between Physical Activity and Glycated Haemoglobin [HbA1c]. CI, confidence interval; LPA, light physical activity; MPA, moderate physical activity; MVPA, moderate-vigorous physical activity; TPA, total physical activity; VPA, vigorous physical activity; I^2,statistic of heterogeneity.

3.5. Sedentary Behaviour

The overall impact SB had on HbA1c highlighted 12/25 (48%) unfavourable associations. The only favourable associations were present for the screen time (schoolwork) construct (3/3; 100%). There were no associations between SB and QoL or any of the secondary outcomes (Tables S4–S7).

The random effects meta-analysis to quantify associations between SB and HbA1c highlighted an insignificant positive association (overall pooled correlation coefficient = 0.12 [95% CI: −0.06, 0.28; I^2 = 86%; p = 0.07]). Subgroup analysis of SB constructs revealed positive association for screen time computer (0.07 [95% CI: −0.11, 0.24; I^2 = 0%]), total sedentary time (0.37 [95% CI: 0.11, 0.58; I^2 = 0%]), screen time television (0.11 [95% CI: −0.09, 0.31; I^2 = 80.5%]) and total screen time (0.12 [95% CI: −0.48, 0.64; I^2 = 0%]). However, a negative association was observed between screen time schoolwork and HbA1c (−0.16 [95% CI: −0.90, 0.81; I^2 = 82.5%]) (Figure 4). Please see Figure S2 for a forest plot of individual studies.

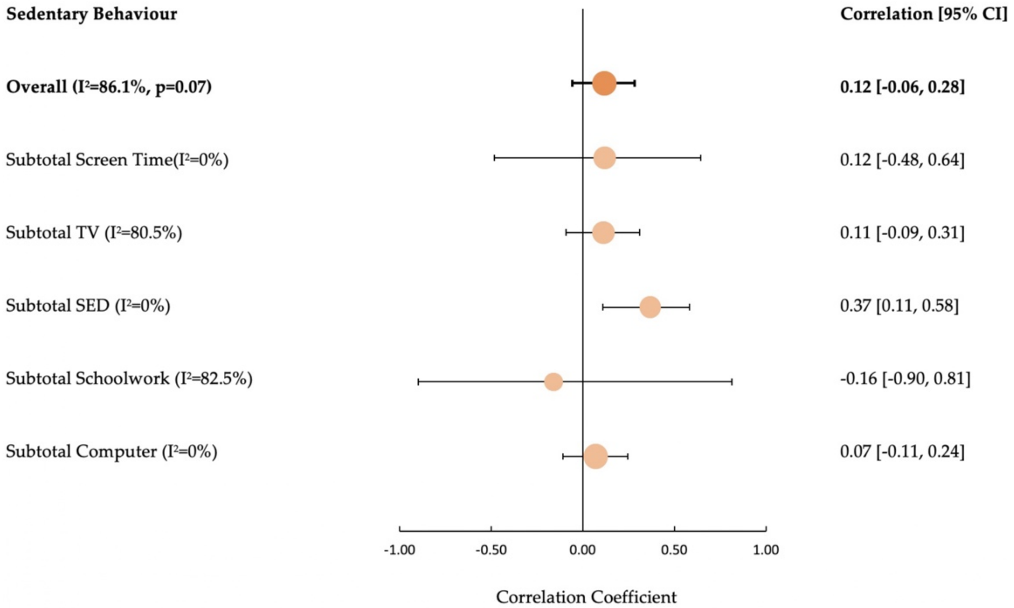

Figure 4. Forest Plot of the Effect of Sedentary Behaviour on Glycated Haemoglobin [HbA1c]. SED, sedentary time; CI, confidence interval; I^2, statistic of heterogeneity.

3.6. Sleep

Sleep's overall impact on HbA1c highlighted 5/32 (16%) favourable and 3/32 (9%) unfavourable associations; the majority were not associated (75%). Sleep's impact on QoL was favourable in 0/2 associations. There was a mix of favourable (5/19) (26%) and unfavourable (3/19) (16%) associations with self-management and favourable associations with depression (5/8) (63%). No associations were observed with anxiety or coping (Tables S4–S7). It was only possible to examine sleep duration construct in the meta-analysis, and this association was not significant (−0.03 [95% CI: −0.21, 0.15; I^2 = 65.9%; p = 0.34]) (Figure 5).

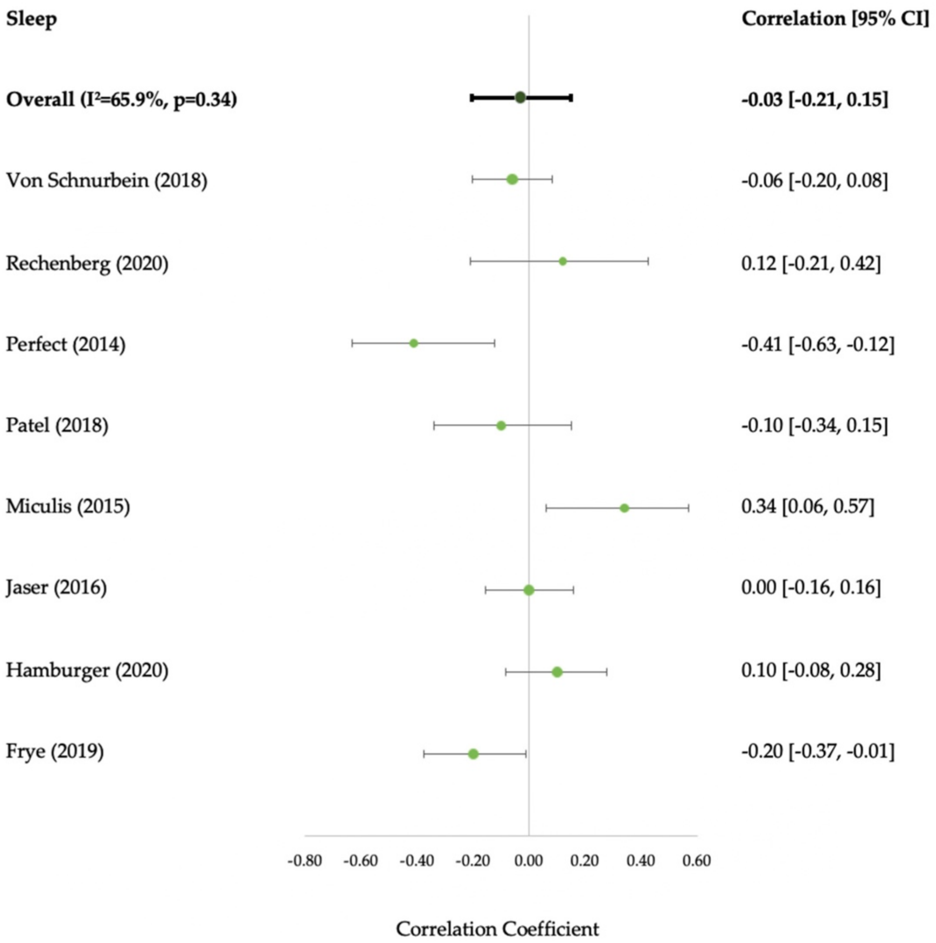

Figure 5. Forest Plot of the Effect of Sleep Duration on Glycated Haemoglobin [HbA1c]. CI, confidence interval; I^2, statistic of heterogeneity [42,45,51,71,81,83,85,98].

3.7. Qualitative Studies

PA was investigated most frequently (*n* = 6; 75%) [104–109] followed by sleep (*n* = 2; 25%) [102,103] with no studies focusing primarily on SB (Supplementary Materials Table S8). Adolescents with T1D and their parents discussed the positive impact PA had in relation to management of glycaemic control in 4/5 studies [104,106,108,109]. This was highlighted by both adolescents with T1D and their parents/caregivers:

> "It helps to sort of control. I don't really know why but I felt that um, if I'm doing more exercise um I can normally keep my levels at a more consistent rate". [Adolescent, p4] [104]

> "What we've learned is that physical activity keeps the spikes and the lows more moderate so you don't fluctuate as much . . . the physical activity just makes that more stable" [Caregiver, p4] [108]

There was discussion from the adolescents with T1D surrounding PA's positive role for improving quality of life in all studies addressing the outcome [3/3] [104,106,107]. This was expressed through the description of positive holistic feelings:

> "I feel quite satisfied", "cheerful", "I like walking because it really relaxes me" [Adolescents, p7] [107]

> "When you're doing exercise you know you're helping your body as well as yourself" [Adolescent, p5] [104]

There was also a glimpse of discussion from parents surrounding PA role in supporting adolescents to cope and how the behaviour might strengthen family functioning [106,109]:

> "a way of getting out his anger" [Caregiver, p6] [109]

> "because it's funner with other people, like you can keep motivated, but you can also have a laugh while you're doing it . . . ', [Adolescent, p153] [106]

Both adolescents and their caregivers expressed fluctuations in glycaemic control as a barrier to obtaining sleep and the anxieties of extreme glucose fluctuations while sleeping [102,103]:

> "Usually [TEEN] sleeps fine, unless his blood sugar's high. Then he's up every couple hours". [Caregiver p123] [102]

> "I panic a lot because one night my blood sugar dropped in the middle of the night and I ended up like having a seizure". [Adolescent, p550] [103]

> "My mother sets an alarm for 2:30 in the morning and she comes and checks me so she doesn't want me to have to get up in the middle of the night". [Adolescent, p550] [103]

Finally, sleep was also discussed in relation to self-management behaviours by adolescents and caregivers [102]. They discuss how curtailments to sleep result in increased lethargy which has subsequent impact on management behaviours (e.g., blood glucose checks). Interestingly, one adolescent highlighted the impact reduced sleep has on their sitting levels:

> "I'm not my usual self. I don't like do things, I just kinda sit". [Adolescent, p546] [102]

> "the lack of sleep would probably cause [her teen] to not be able to keep track of his blood sugars or test when he needs—it probably causes him to be a little lazy about it" [Caregiver, p546] [102]

4. Discussions

To our knowledge, this is the first systematic review to examine the full spectrum of 24-hour movement behaviours in relation to glycaemic control and psychosocial outcomes in adolescents with T1D. We found no studies investigating how combinations of behaviours collectively interact and impact on any of the primary or secondary outcomes.

The results of our study confirmed previous research demonstrating isolated movement behaviours are related to HbA1c and psychosocial outcomes. Both the quantitative and qualitative findings reported higher levels of PA improved glycaemic control and quality of life [110–113]. Additionally, we identified from the qualitative findings the potential benefit of PA on family functioning that was not otherwise highlighted in the quantitative findings. Higher levels of SB worsened HbA1c in most studies, aside from screen time for schoolwork activities which indicated a trend for improved HbA1c. This could be explained by the conscientiousness personality trait associated with homework completion in adolescents which has been found to be related to positive T1D self-management behaviours and thus glycaemic control [114]. The findings from this systematic review highlighted a potential decrease in HbA1c with increased levels of sleep duration; however, the meta-analysis was insignificant and this aligns with previous research [115]. The inclusion of the qualitative studies allowed for a deeper insight into this bi-directional relationship with participants discussing experiences of glycaemic control issues that resulted in interruptions to their sleep. The mixed findings surrounding the direct association of sleep duration and HbA1c might be explained by the mediating effects of self-management activities [116]. Improvements in sleep might improve self-management activities resulting in the subsequent improvement of glycaemic control. Self-management was the most frequently investigated secondary outcome, largely in relation to sleep. We found in quantitative findings both long and short sleep duration, poor sleep quality and delayed timing (e.g., later bedtime) worsened self-management activities. This aligned with our qualitative findings where curtailments of sleep were believed to decrease self-management behaviours.

Although 20.4% of studies reported on two or more movement behaviours, these were examined separately from one another in relation to our outcomes. Most studies investigating more than one behaviour focused on examining both PA and SB. Only 2.4% of the included studies focused solely on SB, a theme consistent with findings from other systematic reviews [111]. The lack of SB focus is also present in current T1D management guidance, illustrated in the International Society for Pediatric and Adolescent Diabetes (ISPAD) PA guidelines. ISPAD recommends youth participate in mostly MVPA and VPA for 60 min/day; however, there are no specific SB guidelines. Instead, minimal SB guidance is made available within the same guidelines, simply stating: "*sedentary lifestyle behaviors should be routinely screened for and discouraged in the diabetic clinic*" [8]. While the research and guidance may suggest SB is deemed less important than PA, optimism lies in the fact these behaviours are often investigated in unison, indicating appreciation for the close alignment of these behaviours. This holds promise for the adoptability of a 24-hour approach by researchers and key stakeholders. Additionally, the qualitative results of this study also indicate adolescents might be willing to adopt a 24-hour approach with one adolescent recognising the interdependency of behaviours (increased levels of sitting after disruptions to sleep).

Research is beginning to investigate the levels of 24-hour movement behaviours relative to one another, rather than as individual entities in populations with chronic conditions [117]. However, no studies to our knowledge have investigated how the behaviours interact and subsequently impact outcomes in adolescents with chronic conditions, including type 1 diabetes. Evidence outside this population consistently illustrates PA, SB and sleep are linked, they impact one another, and this has consequences for physical and mental health [10]. 24-hour movement behaviour guidelines were first published in 2016 with a specific focus on children and youth [118]. These guidelines acknowledge the small percentage MVPA accounts for within the 24 h day (<5%), *move* away from the previous dominant focus on MVPA and additionally consider the percentage of sleep (40%), SB (40%) and LPA (15%) [119]. Adopting a 24-hour approach for adolescents with T1D is a logical step in the management of the condition for several reasons. A 24-hour approach would allow PA to remain one of the cornerstones of T1D management while also placing equal and required emphasis on the benefits of reducing SB. Additionally, although there are mixed findings surrounding the exact relationship sleep may have with glycaemic control, sleep behaviour and diabetes research is gaining traction. This is highlighted by the recent calls for T1D sleep guidance and the widely accepted difficulties both caregivers and adolescents with T1D have with sleep [65,120]. Finally, and importantly, sleep is a necessary behaviour not only to adolescents with T1D but all populations. Other T1D management tools are often prioritised over PA (e.g., diet and medication) despite the behaviour's recognised benefits. Utilising a 24-hour approach where each behaviour is weighted and known to interact would promote the necessity and importance of PA and SB through sleep association. Essentially, PA could 'piggyback' on the necessity of sleep, resulting in higher prioritisation of PA and the associated improvements in outcomes.

Strengths and Limitations

This systematic review provided a comprehensive exploration of the full spectrum of movement behaviours in relation to a range of primary and secondary outcomes, creating novel and holistic findings. Throughout the review process, Covidence meta-analysis software was utilised that is designed to facilitate organisation of studies which enhanced the rigorous assessments of each stage and the reliability of this systematic review's findings. A mixed methods approach was utilised, allowing for in depth examination of effectiveness from the quantitative studies and real-life experience from the qualitative studies. This allowed gaps between effectiveness and experience to be highlighted which exploited possible areas for future research (e.g., PA association with family functioning; the direction of relationship between sleep and glycaemic control) strengthens current findings (e.g., higher PA improves glycaemic control and quality of life) and ultimately enhances usefulness of findings to decision makers.

While the comprehensiveness of this review allowed for a holistic view of associations, there were a range of different terminologies that overlapped, creating difficulty in collating the findings. Studies examining movement behaviours should recognise the multidimensional nature of each behaviour, ensure they are reporting on the exact construct of interest and report this in a manner consistent with previous research or overarching gold standard guidance (e.g., Sedentary Behaviour Research Network or American Psychological Association Thesaurus). This uniformity of reporting would increase the overall strength of findings. While this review incorporated a range of sleep health dimensions, it did not incorporate the recent addition of the regularity dimension, and future research might investigate this dimension in relation to our outcomes. It would have been beneficial to also examine additional outcomes (e.g., hypoglycaemia, hyperglycaemia, risk factors for co-morbidities) to add a further perspective to these results. However, incorporating these outcomes in a review looking at a range of different behaviours was not feasible due to time and resource constraints.

It is important to acknowledge the limitation of HbA1c as an outcome measure. HbA1c only provides an average level of blood glucose over the past 2–3 months and little information can be ascertained regarding the frequency, duration or amplitude of intra-day (within-day) and inter-day (between-day) glycaemic excursions [16]. CGMs have increased in availability and accuracy over the last century and have facilitated diabetic glycaemic control. They produce real-time measurements of the glucose level excursions HbA1c overlooks, allowing for immediate action to address raised or lowered glucose levels that can subsequently prevent potential acute incidents (e.g., hypoglycaemia and hyperglycaemia). However, in this systematic review minimal studies investigated the movement behaviours' impact on glycaemic control assessed via CGM metrics despite the increased availability of the device and the recommended standardised metrics that aim to guide clinicians, patients and researchers in using, analysing, and reporting CGM data.

5. Conclusions

This systematic review highlighted that no studies to date have investigated how combinations of behaviours collectively interact and impact on any of the primary or secondary outcomes in adolescents with T1D. Monitoring the full spectrum of 24-hour movement behaviours would allow for a comprehensive understanding of how the cumulation and weighting of each behaviour might interact and impact on important outcomes for adolescents with T1D. Future research should investigate the association between 24-hour movement behaviours (measured via accelerometer), glycaemic control and psychosocial outcomes. Additionally, measuring glucose control via both HbA1c and CGM glucose metrics would aid in the comprehensive investigation by providing a detailed objective and continuous pattern of glucose over the full 24-hour period. Finally, qualitative studies investigating the knowledge, awareness and feasibility of a 24-hour movement behaviour approach would aid in understanding how adolescents with T1D might adopt this type of approach.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijerph20054363/s1, Glossary of Terms S1; Search Strategy S2; Table S1: Inter-Rater reliability between reviewers; Table S2: Characteristics of Quantitative Studies; Table S3: Quality Assessment; Tables S4–S7: Movement Behaviours Associations with Primary and Secondary Outcomes; Table S8: Characteristics of Qualitative Studies; Figure S1: Forest Plot of Physical Activity Individual Studies; Figure S2: Forest Plot of Sedentary Behaviour Individual Studies.

Author Contributions: M.P. designed the research, conducted the search, screened the studies, extracted, analysed and interpreted the data and wrote the paper. X.J., A.K. and M.C. made substantial contributions to study conception and design of the research. S.M., E.R. and W.H. screened the studies and extracted study data. All authors have read and agreed to the published version of the manuscript.

Funding: The lead researcher M.P. received a stipend for this Ph.D. project through the University of Strathclyde Student Excellence Awards. The APC was funded by the University of Strathclyde Institutional Open Access Fund (IOAF).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: M.C. is a consultant for Signfier Medical Technologies, but this activity is not related to the content of this article. The remaining authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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5. Chapter Summary

Chapter one summarised the systematic review and meta-analysis that established the foundation of this thesis. Importantly, the systematic review highlighted no quantitative or qualitative study investigating how combinations of all three behaviours within the 24-h MB paradigm collectively interacted and impacted on outcomes. To extend the insights from the systematic review, the next phase required data collection methods that were rigorous, ethically sound and sensitive to the needs of a protected population. Careful planning of recruitment procedures and ethical safeguards ensured that high quality data could be obtained for the empirical studies that follow. Chapter two therefore outlines this data collection process in detail, describing how quantitative and qualitative data were collected in parallel over a six-month period.

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Chapter 3 - Data Collection, Recruitment Challenges and Ethical Reflections

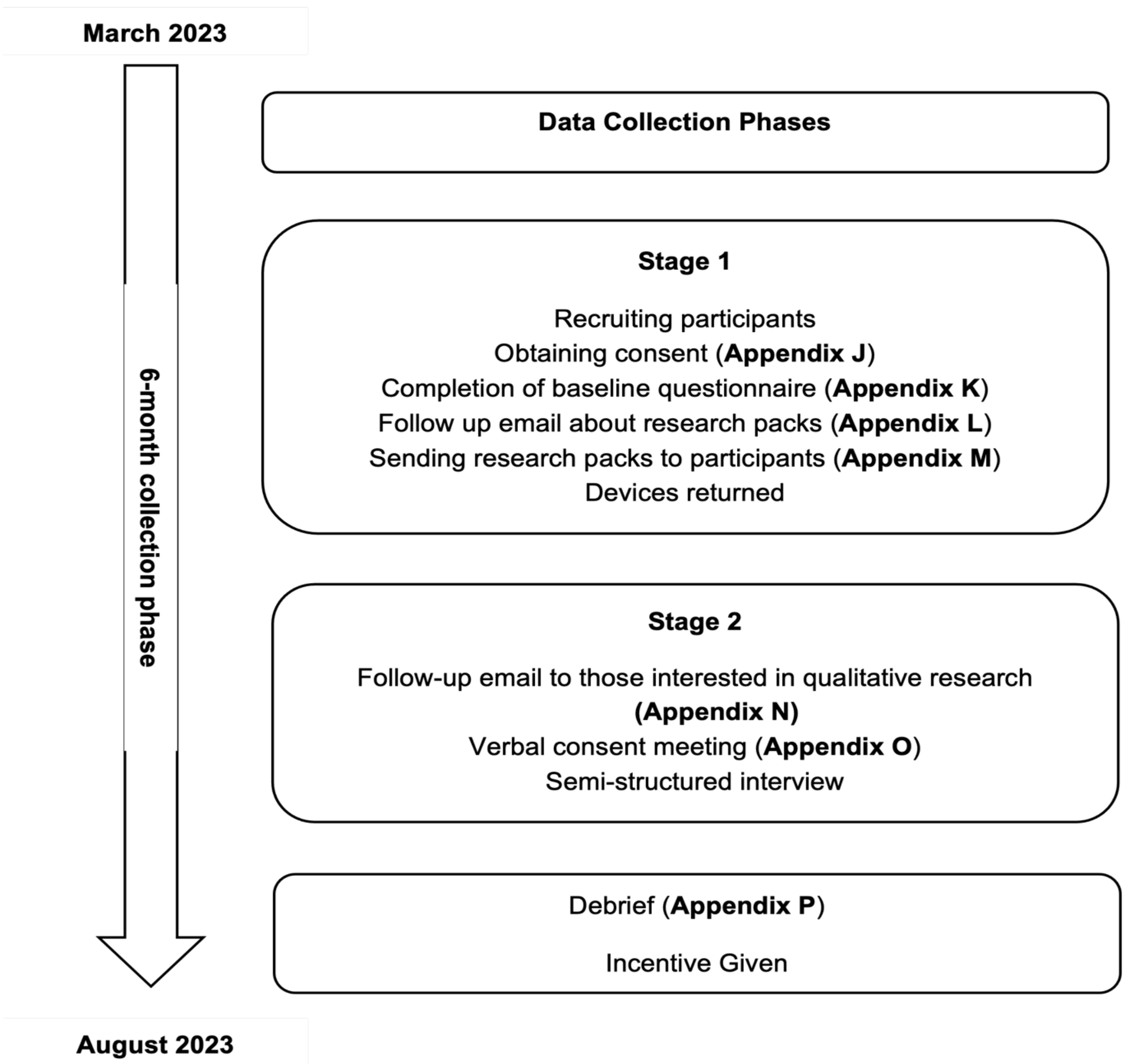
1. Chapter overview

This chapter outlines the data collection methods used for the qualitative and quantitative studies presented in this thesis. Specifically, this chapter will reflect on early missteps and critical adaptations made after an initial data collection pilot, which faced low engagement and high attrition. Key barriers to data collection included communication to target this specific population, obtaining consent online and lack of a structured online recruitment strategy grounded by evidence-based practice. Finally, the chapter discusses ethical reflections surrounding the discomfort of navigating online spaces as an outsider (i.e. not living with T1D), balancing participant recruitment goals as a student researcher with community sensitivities, and the emotional toll of witnessing participant struggles. The chapter concluded by underscoring the importance of culturally sensitive, ethically sound recruitment methods which would provide a foundation for future studies targeting vulnerable youth populations.

2. Overview of data collection methods

Both the quantitative (study 2) and qualitative (study 3) data collected for this thesis were collected simultaneously over a 6-month period between March 2023 and August 2023. Data collection was split into two stages. The first stage was centred around recruiting participants, obtaining consent, completion of the baseline questionnaire and sending research packs to participants (i.e. accelerometers, research guidance). Part of the baseline questionnaire asked participants if they would like to participate in further research associated with the Balancing Healthy Days Study. The second stage of data collection involved sending a follow up email to the participants showing an interest in the further research to select a time and date to obtain verbal consent and conduct the semi-structured interview (**Figure 3.1**). Once participants returned their accelerometer device and valid data was recorded, they were sent a £10 amazon voucher. In total there were 39 participants who completed the questionnaire, 32 that returned accelerometers with data recorded and 15 participants who conducted the qualitative semi-structured interviews.

Figure 3.1: Flow chart of data collection stages



3. Development of an online recruitment strategy

An important step for this thesis was the piloting of the initial data collection methods by Masters students at the University of Strathclyde. This pilot revealed specific challenges resulting in low recruitment and retention rates. These challenges arose from the absence of a structured recruitment strategy specific to this population that was grounded by evidence-based practices.

Therefore, a recruitment strategy was developed post pilot using the AIDA (Attention, Interest, Desire, Action) model and the ACME (Audience, Channel, Message and Evaluation) framework. The AIDA model is one of the most widely used marketing strategies and explains the four cognitive stages consumers experience when faced with a new idea, advertisement or sales promotions (Michaelson & Stacks, 2011; Pashootanizadeh & Khalilian, 2018). It describes how you get attention, attract interest, create desire and then take action, which in this case is taking part in the research study and has been utilised to develop social media strategies (Hassan, Nadzim, & Shiratuddin, 2015).

The ACME framework is used for health communication campaigns and highlights the need to identify the primary audience while considering socioeconomic, personal and behavioural characteristics. The channel component refers to the communication channels that best targets the audience. The message component refers to creating messages specific to the audience and evaluation refers to the importance of integrating evaluations throughout the campaign to monitor progress (Kreps et al., 2022; Noar, 2012). Incorporating both marketing health communication frameworks allowed for a more targeted approach in engaging and retaining participants. The recruitment strategy utilised for this research was composed of four key stages: 1) Understanding the audience (engagement and retention strategies and online consent considerations); 2) Strong and Consistent Messaging; 3) Communication Content, Platforms and Partners and 4) Evaluation.

3.1 Stage One: Understanding the audience (engagement, retention and consent)

Research has identified several key barriers and facilitators influencing adolescent participation in health research. Jong, Stevenson, Winpenny, Corder, and van Sluijs (2023), conducted a qualitative study exploring adolescent (15–20 years) perspectives on engagement and retention in a longitudinal health study. Their findings highlighted that motivators for participation included opportunities for social interaction (e.g., joining with peers), receiving personalised feedback, and access to financial incentives. Conversely, perceived high commitment, poor timing, and general disinterest were cited as barriers. Adolescents expressed a clear preference for recruitment via social media platforms, especially when messaging was tailored to their individual motivations. They also favoured hybrid models of data collection, combining brief (20–30 minute) online activities with occasional in-person contact, ideally with a consistent and non-judgemental researcher. The ability to exercise autonomy and choice, alongside receiving appropriate financial incentives, was seen as key to sustaining engagement.

Effective recruitment of adolescents requires more than digital outreach alone. Schoeppe, Oliver, Badland, Burke, and Duncan (2014), emphasised the importance of developing relationships with community partners, offering accessible and transparent study information, and securing the support of key stakeholders such as parents, caregivers, and schools. Establishing a clear study identity and employing an ethical and well-structured consent process further strengthened recruitment. Namageyo-Funa et al. (2014), similarly underscored the value of engaging gatekeepers (i.e. those with access to or influence over potential participants, such as parents/caregivers) and diversifying recruitment channels (e.g., platforms, media type) while maintaining a deep understanding of the target population.

In practice, personal engagement with caregivers and the wider support network, such as charity representatives, has been shown to improve recruitment and retention outcomes (Mendelson, Sheridan, & Clary, 2021). Complementary strategies, including digital outreach, word of mouth, and snowball recruitment through existing participants, have also proven effective (Parrish, Duron, & Oxhandler, 2017; Romain, Hendrick, Reed, Staiano, & Harris, 2020). Central to retention efforts is the cultivation of trust and rapport through consistent, personable contact. Studies have highlighted the importance of maintaining a single point of contact with strong interpersonal skills, being responsive and appreciative and allowing time for peer socialisation (Hanna & Hansen, 2020; LaRose et al., 2016; Vogel, Comtesse, & Rosner, 2020). However, more is not necessarily better as evidenced by Teague et al. (2018) and Mendelson et al. (2021) who found that an increased number of retention strategies did not guarantee improved outcomes. Instead, approaches that reduced participant burden such as offering flexibility in how and when data is collected were most effective.

Incentives remain a critical component of adolescent engagement and retention. Financial incentives, in particular, have been shown to significantly enhance participation, though the return on increased incentives diminishes over time (Laurie, 2007). Strategic incentive boosts have been successful in engaging underrepresented or high-effort participants (McGonagle, Sastry, & Freedman, 2023). However, the use of incentives with adolescents presents ethical challenges. Adolescents often expect and appreciate incentives for their involvement

(Calderwood, 2014; Jong et al., 2023) but concerns persist around their potential coercive impact, especially for younger participants. Similarly, caregiver-directed incentives may inadvertently pressure adolescents into participation. These ethical considerations must be weighed against the need to compensate participants fairly and equitably. Disparities in incentive rates between adolescents and adults for equivalent contributions may risk age-related inequity. While non-monetary incentives, such as vouchers, gift cards, or study-branded items, are sometimes offered as alternatives, evidence suggests they are generally less effective than direct financial compensation (Murray & Xie, 2024).

Research elements that deter adolescents, such as lengthy questionnaires or fragmented communication, are likely to be even more discouraging for those managing a chronic illness, further reducing the likelihood of participation or study completion. Additionally, the use of research language (i.e. using research/medical jargon) is a common barrier to adolescent recruitment in health research (Franke et al., 2022). Describing the research in a way that relates to the population of interest can improve engagement significantly. Simplifying and being mindful of potentially offensive or ignorant language (e.g., consulting diabetes UK ‘Language Matters’ resource to avoid inflammatory T1D terms), reducing the length of study information and changing the style to informal improves participant recruitment (Calderwood et al., 2015).

Obtaining consent from adolescents online presented key challenges due to the different consent requirements for specific ages within the 11–18 year range. Parental/caregiver consent is required for adolescents aged 11 years while ≥12 years have the capacity to consent if, after assessment, they have a clear understanding of what they are asked to do (i.e. they are Gillick competent). While consent from an adolescent ≥12 years is legally valid, it is good practice to also include the parent/caregiver. If the adolescent does not have a clear understanding of the research and their expectations being involved in the research, then consent will need to be obtained from the parent/caregiver. However, adolescents aged 16–18 years can give consent (NHS Health Research Authority., 2025).

Validation of the consent obtained online for adolescents 11 years old was required to ensure consent was indeed obtained from parents/caregivers. Similarly, validation of consent from adolescents 12–15 years was required to ensure they did indeed have a clear understanding of the research. To do this, a verbal consent meeting was conducted with all adolescents 11–15 years and their caregivers/parents (NHS Health Research Authority., 2025). Although this process bypassed any ethical concerns regarding legal capacity to consent it increased the research burden for participants by complicating recruitment and prolonging study timelines which is a key barrier for adolescents (Jong et al., 2023).

However, an important learning from the pilot data collection was that the initial verbal consent meetings provided valuable opportunities to build rapport and trust with participants, which is particularly important due to the challenges of forming authentic connections through online methods (Murray & Xie, 2024). These early interactions allowed the researcher to be more personable and relatable to adolescents and caregivers, which appeared to support participant retention and facilitated more meaningful engagement. Additionally, using these verbal consent meetings to build initial rapport facilitated conversation with more reserved adolescents participating in the semi-structured qualitative interviews. Despite these improvements, this experience highlighted the ongoing challenge of balancing ethical requirements with participant burden, particularly when working with mixed-age adolescent groups online.

3.2 Stage Two: Strong and consistent messaging

The study was branded as *The Balancing Healthy Days Study* to establish a relatable and positive identity. The communication strategy addressed key elements of the AIDA framework. Firstly, by generating interest by clearly explaining the purpose of the research; secondly, by creating desire through the presentation of incentives for participation; and thirdly, prompting action via a concise, three-step guide to enrolment. The message also included a direct link to begin the process and contact details for the lead researcher, further facilitating ease of participation.

Maintaining consistency across all social media platforms is critical when recruiting research participants, particularly in fostering trust, recognition, and engagement. Consistent communication both in messaging and visual identity creates a sense of familiarity and reliability, which are essential for building credibility with potential participants. Research has shown that organisations perceived to have a consistent visual identity are evaluated more positively in terms of innovation, credibility, and distinctiveness, and are more likely to be seen as trustworthy and reputable (Kaur & Kaur, 2021). This familiarity positively influences individuals' attitudes toward the organisation and their intention to engage with it. For participant recruitment, especially among sensitive or hard-to-reach populations such as adolescents or clinical groups, consistency in branding and messaging across platforms enhances the likelihood of trust, ultimately increasing recruitment efficacy.

3.3 Stage Three: Communication content, platforms and partners

Many health research studies involving adolescents use social media as a recruitment medium due to its wide use by the population (Plaisime et al., 2020). There are several different social media platforms available with Instagram reported as the most popular social media platform in adolescents, followed by Facebook, TikTok, and Twitter (Demers-Potvin et al., 2022). However, the social media platform adolescents utilise is in constant flux and researchers utilising social media must be aware of faster growing platforms that might be more efficient in the recruitment process. For example, TikTok is the fastest growing social media platform globally among children and young people allowing users to consume and create short videos between 15–60 s in length (McCashin & Murphy, 2023). Short videos have become a key medium for disseminating information to adolescents by effectively utilising short periods of time to deliver key content specific to the audience of interest (Zeng, Yao, & Ma, 2025).

Utilising short videos in adolescents reduces the need for lengthy text describing the study, which is a known recruitment barrier in this population (Calderwood et al., 2015). Additionally, a short video offers an opportunity to build rapport with participants and make the research more personable by having the main researcher describe the study. This is particularly important as building relationships between researcher, participants and related stakeholders (i.e. parent/caregiver) can be difficult when utilising online recruitment and can make significant impacts on recruitment and retention (Murray & Xie, 2024). Therefore, a short video was created of the lead researcher describing the research which was then used alongside a link to the baseline questionnaire and distributed across Instagram, Facebook and X (formerly known as Twitter) platforms.

The online recruitment strategy for this study also utilised diabetes related charities (Diabetes UK and JDRF), T1D influencers (Diabetes Sisters, sports personalities, comedians) and relevant FB groups. Having charities associated with the research increased the credibility of the research, which is particularly important when trying to build rapport and trust with both participants and caregivers/parents. The use of influencers are considered as crucial components to reach the attention of adolescents within online marketing strategies (Alves de Castro, OReilly, & Carthy, 2022). Additionally, T1D role models such as celebrities and influencers, are perceived to empower young people and engage with diabetes content and conversations (Berry et al., 2024). Facebook allows users to create ‘groups’ that users can engage with and offers users specific advice and tips on how to create impactful groups. The key messages used in advertising these Facebook groups are their ability to create community. There are a number of Facebook community groups available for adolescents living with T1D which might be explained due to the known benefits of participating in community groups (i.e. social support and reduced disease burden).

3.4 Stage Four: Evaluation

A critical component of assessing the effectiveness of recruitment strategies is the implementation of systematic evaluation. In this study, recruitment success was primarily measured by the number of participants who completed the questionnaire. Particular attention was paid to the timing of communications and the specific social media platforms used, in order to identify which channels generated the highest levels of engagement within the target population. In addition to participant data, social media analytics were employed to gauge the reach and interaction with recruitment messages. Platforms such as X (formerly Twitter) provide useful metrics, including the number of impressions, retweets (indicating message amplification by others, such as charities or influencers), and likes (which can signal endorsement or interest). Interpreting these metrics enables real-time adaptation of recruitment strategies and offers opportunities for proactive engagement. For example, responding to influencer shares to enhance visibility and foster a more personable and interactive presence. Establishing this type of reciprocal communication can help build trust and a stronger connection with the audience, ultimately supporting sustained interest and participation.

4. Ethical reflections and moral barriers

Navigating recruitment for health-related research without NHS ethics approval presents a complex emotional and ethical terrain, particularly for student researchers attempting to engage clinical populations in informal online spaces. In efforts to recruit adolescents living with T1D significant discomfort emerged from feeling of 'lurking' in social media groups where deeply personal experiences were shared by individuals and their families, spaces that serve primarily as support networks rather than research recruitment pools (Franzke, Bechmann, Ess, & Zimmer, 2020). This positioning as an outsider (i.e. without lived experience of T1D) highlighted feelings of confliction between the need to promote research and the need to respect community boundaries. The emotional weight of observing real life struggles while remaining largely invisible and inactive within the group influenced a cautious approach to engaging with the population which sometimes resulted in self-censorship and reduced engagement. This internal conflict underscores broader systemic barriers for students who might lack formal pathways (i.e. NHS) for improved participant recruitment. The absence of a student researcher friendly recruitment process not only hampers data collection but can impose considerable emotional labour on researchers themselves who may have to navigate sensitive spaces and environments. There is an urgent need for clearer, compassionate guidance that acknowledges both the vulnerabilities of potential participants and the ethical strain placed on student researchers, including frameworks that promote transparency, positionality, and respectful community engagement.

5. Chapter summary

This chapter outlined the key challenges, adaptations, and lessons learned in developing an online recruitment strategy for adolescents living with T1D. Initial barriers around engagement, consent, and retention led to a responsive, evidence-based approach. These considerations were essential for gathering both quantitative and qualitative data for this thesis and should be carefully considered by future researchers working with vulnerable youth populations in digital contexts. The strategies developed here laid the foundation for the studies that follow in chapters four and five.

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Chapter 4 - Study Two, Quantitative Exploration of 24-h Movement Behaviours

1. Chapter Overview

The aim of this chapter is to present the second study of this PhD, an exploratory study investigating a sample of UK adolescents living with T1Ds 24-h MB levels using wrist-worn accelerometery. This chapter presents a comprehensive review of the 24-h MB measurement tools, a comparison of self-report and wearable-based data collection methods, and a detailed exploration of specific accelerometer processing decisions in relation to 24-h MBs. Additionally, an overview of analytical approaches used in 24-h MB research is presented. Finally, a synthesis of the key decisions and their rationales are stated prior to the introduction of study two.

2. Measuring 24-hour movement behaviours

Accurate measurement of PA, SB and sleep is essential to ensure the credibility of research findings, which ultimately informs interventions and evidence based clinical guidance. There are several types of movement behaviour measurement methods, each with their strengths and limitations. Several factors should be considered when choosing a measurement method including 1) the reliability and validity of the measure; 2) the type of study (e.g., epidemiological vs clinical); 3) the population of interest and 4) the outcome of interest (Dalene & Ekelund, 2023).

2.1 Movement behaviour measurement gold standards

For each movement behaviour, a criterion or 'gold standard' measure exists that is highly valid and is considered the best available standard for measuring a specific behaviour. For PA, the doubly labelled water (DLW) technique is considered one of the gold standard for measuring total daily energy expenditure in free-living environments over a period of several day to weeks (Westerterp, 2018). This technique involves administration of labelled water, containing isotopes of oxygen and hydrogen, which are monitored over time to estimate carbon dioxide production and subsequent energy expenditure (Melanson Jr, Freedson, & Blair, 1996). Indirect calorimetry is another gold standard for measuring energy expenditure, however, is often conducted in small chambers or requires participants to wear a mask (Mtaweh, Tuira, Floh, & Parshuram, 2018). Although DLW and indirect calorimetry are well established methods for the measurement of energy expenditure, they give no detail on the type, duration, intensity and context of PA which is particularly important on a population level scale where national guidelines emphasise the importance of obtaining certain intensities of activity.

Direct observation is considered a highly valid measure for SB and involves a trained observer watching participants over a specified length of time and classifies behaviours based on predetermined criteria (Aunger & Wagnild, 2022; Kozey-Keadle, Libertine, Lyden, Staudenmayer, & Freedson, 2011). For sleep, polysomnography (PSG) is the current gold standard. It measures brain activity via electroencephalography (EEG), eye movements via electrooculography (EOG), muscle activity via electromyography (EMG), heart electrical activity via electrocardiography (ECG), airflow and respiratory effort and blood oxygen levels. To achieve this, individuals typically spend the night in a sleep laboratory in controlled settings under the continued supervision of a sleep technician. However, at home PSGs are becoming more available (Rundo & Downey III, 2019). Although PSG is highly valid and reliable it is frequently too time consuming and expensive to use in larger studies and difficult to use if there is a desire to measure sleep over an extended period of time.

A number of alternative movement behaviour measures have been produced and validated against each of the movement behaviours benchmarking standards and can typically be categorised into self-report and wearable measures.

2.2 Self-report measures

Self-report measures refer to a wide variety of tools utilised to gather information on participants behaviours, or the behaviours of others (e.g. diaries, logs, questionnaires, recalls). Historically, these have provided the evidence base that shape global movement behaviour guidelines and have been used in a variety of settings (e.g., population surveillance, interventional studies, health assessments and observational research) (UK Chief Medical Officers, 2019). Perhaps the greatest strength of self-report is the associated low-cost of gathering information when compared to their device-based counterparts in larger scale studies. Additionally, self-report measures can understand the domains of behaviours (e.g., leisure time PA, type of screen time activity) and participants subjective perceptions of a given behaviour (e.g., sleep quality). However, the greatest limitation of self-reports is often attributed to reporting errors arising from factors such as bias (i.e. recall, social desirability, response and subjective perception biases), retrospective reporting and simple misinterpretation of questions (Healey et al., 2020; Ji & Liu, 2016; Sattler et al., 2021). It is therefore important to ensure the self-reporting measures chosen have been validated to use for the specific population under investigation to minimise potential errors.

There are a number of validated self-reported tools that have been developed over the years to obtain movement behaviour information in adolescents (Cespedes et al., 2016; Chinapaw, Mokkink, van Poppel, van Mechelen, & Terwee, 2010; Helmerhorst, Brage, Warren, Besson, & Ekelund, 2012; Lauderdale, Knutson, Yan, Liu, & Rathouz, 2008). However, most of these tools have been developed to assess one or two of the 24-h MBs opposed to all three behaviours. For example, the International Physical Activity Questionnaire modified for Adolescents (IPAQ-A), Adolescent Sedentary Activity Questionnaire (ASAQ) and the Pittsburgh Sleep Quality Index (PSQI) which, has been adapted to use in young people and adolescents (AYA-PSQI-S) (Buysse, Reynolds III, Monk, Berman, & Kupfer, 1989; De la Vega et al., 2015; Hagströmer et al., 2008; Hardy, Booth, & Okely, 2007). Each of these measures differ on the time period investigated (e.g., past day, week, month, year or lifetime), activity domain (e.g., leisure, household, transportation, school/occupation), length of questionnaire, administration mode (e.g., interviewer or self-administered) and outcome measurement (e.g. kilocalories, MET-hours). This lack of uniformity makes it particularly difficult to combine movement behaviour tools in a bid to obtain information on all 24-h MB. Additionally, it is unlikely that the sum of all movement behaviours collected using a variety of different measures will equal 24-hours (or other finite total). This would then present subsequent barriers in relation to analysing data in a way that respects the 24-h MB paradigm, specifically, that components are relative to one another and need to be examined accordingly (i.e. compositional analysis).

Since the adoption of 24-h MB guidelines, there has been an increased interest and campaign for self-reporting tools that align with the 24-h MB paradigm. Šuc, Einfalt, Šarabon, and Kastelic (2024), conducted a systematic review to identify validated self-reported tools used for assessing movement behaviours across the whole 24-h day in adolescents (12–17 years), adults (aged 18–64 years) and older adults (65 years and older). Additionally, they aimed to review the self-reported tools measurement properties and attributes. The systematic review highlighted 12 self-reporting tools available to assess 24-h MB and these were determined valid and reliable to use in epidemiological studies and population surveillance. However, this review was limited to studies that validated estimates of movement behaviours across the full 24-hour day, meaning the number of included studies was reduced since studies that did not validate all components of the 24-h day (sleep, PA and SB) were not included. Perhaps the most important finding from this systematic review in relation to this thesis is that despite including adolescents (12–17 years) in the search strategy, none of the tools identified were valid and reliable to use in the adolescent population. Another systematic review conducted by Rodrigues et al. (2025) aimed to systematically review the literature on measurement properties of questionnaires available measuring 24-h MB specifically in children and adolescents. They identified 37 questionnaires however, all of these had insufficient measurement properties and none considered the 24-h MB paradigm.

Although there are few tools developed to measure 24-h MB in adolescents (Alkhraiji, Barker, & Williams, 2022; Song et al., 2021) none were deemed valid or reliable in assessing movement behaviours from a 24-h MB perspective from either of the aforementioned systematic reviews. Given the rise in 24-h MB guidelines for adolescents globally, it would be appropriate for a self-reporting tool to be developed for this population that considered the requirements of a 24-h MB paradigm. Currently, device-based measures are the preferred option for measurement considering a 24-h MB perspective, however capturing this information on a population level can be costly.

2.3 Wearables

Wearables used to measure movement behaviours are often small, non-invasive and capable of capturing real time objective data which allow them to bypass many of the self-report limitations (i.e. bias, retrospective reporting, misinterpretation of questions). Although these wearables are capable of obtaining biological (i.e. awake or asleep), postural (i.e. lying, sitting or upright) and intensity (i.e. light, moderate or vigorous) dimensions, they are less effective at capturing contextual information compared to self-reports, are often more expensive and pose greater logistical challenges (Giurgiu et al., 2022). Wearables have been used in all age groups and across a variety of research settings (i.e. laboratory and free-living) (Giurgiu et al., 2025) and are now being utilised in larger scale studies for measuring population level movement behaviours (e.g., the UK Biobank Study and the National Health and Nutrition Examination Survey (NHANES).

There are many decisions researchers should make when conducting health research using wearables but perhaps the most important consideration is selecting the most appropriate validated device relevant to the population and outcomes of interest. However, the rapid advancement of wearable technology poses significant challenges in ensuring that each device is adequately validated for use within specific populations and settings. The time required to conduct and publish validation studies often lags behind the pace of technological development, creating a persistent issue for researchers. As new and potentially superior devices are introduced to the market, validation studies for existing wearables may become outdated before they are even completed, making it increasingly difficult to maintain scientific rigor (Rosenberger, Buman, Haskell, McConnell, & Carstensen, 2016).

Across all age groups, adolescent have the lowest number of 24-h MB measurement validation studies available, specifically in free living conditions (Giurgiu et al., 2022; Giurgiu et al., 2025). Furthermore, most validation studies focus on children and adolescents without health conditions, making it difficult to determine whether wearables perform with the same accuracy and reliability in populations with health conditions (Giurgiu et al., 2022). This raises concerns about the applicability of wearable devices for T1D populations. As a result, wearable derived movement data in this group may be prone to misclassification, limiting its reliability for both research and clinical decision-making. Finally, most wearables have only been validated for a single dimension/behaviour and although wearables have been used to assess the full spectrum of 24-h MB, there is no single device validated to measure all three behaviours in adolescents (Giurgiu et al., 2022).

Overall, there is a general lack of validation studies for 24-h MB, a gap that is particularly pronounced in adolescents and even more so in underrepresented groups such as those living with T1D. In this absence, researchers must be comprehensive when making decisions and create clear rationales for accelerometer processing and analytical decisions as these decisions directly impact movement behaviour data.

3. Data collection and analytical considerations

Researchers utilising wearables must consider important data collection and analytical decisions. **Table 4.1** highlights the key accelerometer considerations that require evaluation to ensure the most accurate and meaningful assessment of 24-h MBs.

Table 4.1: Key accelerometer decisions.

Accelerometer Considerations	Description
Wear location	Body site where the device is worn (e.g., wrist, hip), affecting signal interpretation.
Activity cut-points	Thresholds used to classify activity intensity (e.g., sedentary, light, MVPA).
Sleep algorithms	Algorithms to estimate sleep duration and quality.
Non-wear time	Time when the device is not worn, identified through consecutive 0 counts within specified epochs or algorithms.
Valid day	Minimum wear time required in a day for data to be included in analysis.
Valid week	Number of valid days needed to represent typical weekly behaviour.
Sampling frequency	Number of acceleration samples collected per second (e.g., 30 Hz, 100 Hz).
Epoch length	Time window over which acceleration is summarized (e.g., 1s, 15s, 60s).
Axis analysed	The dimension(s) of acceleration used (e.g., vertical, vector magnitude).

3.1 Wear location

Most estimations of energy expenditure have been derived from waist worn estimations however, wrist worn accelerometers are gaining popularity as an alternative. The UK Biobank study is a large prospective study with over 500,000 participants aged 40–69 years, recruited between 2006–2010. From 2013 to 2015 this study introduced accelerometery and a sub-set of the participants (n=100,000) were asked to wear a Axivity AX3 accelerometer on their dominant wrist for 7-days, 24-hours a day without removing the device (Doherty et al., 2017). Additionally, the US NHANES initially employed waist worn accelerometers to participants (≥6 years) during all non-sleeping hours for seven days from 2003 to 2006. This was considered the largest scale accelerometer deployment at that time. However, in 2011 NHANES transitioned to wrist worn accelerometery, asking participants to wear an ActiGraph GT3X+ on their non-dominant wrist for 7-days, 24-hours a day including during sleep (Troiano, McClain, Brychta, & Chen, 2014).

There are a number of reasons why these larger scale studies have opted for the wrist worn accelerometer placement as opposed to waist worn. Wrist worn accelerometers have been shown to be valid in estimating PA energy expenditure in free-living situations, which was the initial primary outcome for each of these large-scale studies (White, Westgate, Wareham, & Brage, 2016). Additionally, the growing interest in 24-h MB research and the shift toward 24-h MB guidelines highlighted the need to obtain relevant sleep metrics, and wrist actigraphy is a well validated measure of sleep duration and quality in adults and adolescents (Meredith-Jones et al., 2024; Morgenthaler et al., 2007). However, perhaps the greatest rationale for utilising wrist worn accelerometery is the increased wear compliance. Troiano et al. (2014) reported that compliance was recognised as a major issue due to the discomfort or inconvenience of wearing a device on the hip over time and forgetting to put the monitor back on after taking it off at night. Since NHANES switched from waist worn accelerometery to wrist worn, compliance increased drastically. In the 2003–2004 cycle of NHANES when devices were worn on the waist, approximately 40–70% of participants by age group provided at least six days of data with at least 10 hours of wear time and a large effect of age on wear compliance was evident. In contrast, in the 2011–2012 cycle with wrist wear, 70–80% of participants provided at least six days of data with at least 18 hours of wear time and little difference by age was apparent.

In studies investigating wear placement compliance in adolescents specifically, Scott et al. (2017) investigated the comparability and feasibility of wrist and hip worn accelerometers among free living adolescents (13–14 years) and found adolescent compliance was significantly higher with wrist placement, with participants reporting that it was more comfortable and less embarrassing to wear on the wrist. However, compliance to wrist worn accelerometery is still challenging for adolescents as they report issues surrounding comfort, device size, interference with daily routine and social perception (Grimes et al., 2025). These compliance issues will be even more prominent in adolescents living with T1D due to the technology burden already experienced by this population. Technology is often concealed to avoid unwanted attention in this population and introducing an additional wearable device could result in increased social anxiety and device fatigue (Morrow, Kirk, Muirhead, & Lennon, 2023). There are currently no studies investigating the most appropriate wear location (e.g., on a site more hidden) within this population, which might be explored to reduce compliance issues and enhance data collection. This is particularly pertinent given that many adolescents with T1D routinely wear insulin pumps or related devices at the waist (e.g. via belts or pouches).This may limit the feasibility of additional waist worn monitors and further support the selection of wrist worn accelerometers in this population (Biester et al., 2024).

Although large-scale studies such as the UK Biobank and US NHANES both employed wrist worn accelerometery to capture 24-h MB, they differed in wrist placement. The UK Biobank used the dominant wrist, while NHANES selected the non-dominant wrist. At the time these protocols were implemented, there was no clear consensus on which wrist was optimal for movement behaviour measurement - a lack of agreement that persists today (Eslinger et al., 2011; Phillips, Parfitt, & Rowlands, 2013; Zhang, Rowlands, Murray, & Hurst, 2012). NHANES selected the non-dominant wrist partly based on established practices and evidence from past sleep research (Troiano et al., 2014). However, more recent research in adults suggests that wrist side may not critically impact sleep variable estimates (Driller, O'Donnell, & Tavares, 2017). When it comes to adolescent populations, evidence remains sparse. One of the few relevant studies found that wrist worn location did not significantly influence PA outcomes in free living adolescents (12–17 years) (Davila, 2011). This indicates that, at least for PA monitoring in youth, wrist location may be of minimal consequence, but further research is needed to confirm this across SB and sleep outcomes.

Although there are numerous benefits to using wrist placement over hip placement for adolescents (i.e. increased compliance and validated measure of sleep for 24-h MB analysis), there are associated data processing challenges especially when capturing the full spectrum of movement behaviours over a full 24-hour day. Specifically, it can be difficult to distinguish between sleep, SB, and non-wear time. These issues are more pronounced in wrist worn devices compared to hip worn accelerometers, as the wrist remains more active during SBs (e.g., gesturing while sitting) and can show small movements during sleep, complicating accurate classification. Therefore, it is crucial the correct processing methods and/or algorithms are utilised for the population under investigation to ensure accurate estimates (Pulakka et al., 2018).

3.2 Cut-points and sleep algorithms

Cut-points are utilised to classify activity into intensity categories (i.e. SED, LPA, MVPA etc). To increase the validity of output from these cut-points, it is advised to utilise the same methodological decisions from the original validation/calibration studies. This is often hard to do because device models and firmware may differ, detailed protocols are not always fully reported, and the logistical constraints and available resources can vary substantially between research projects. As a result, researchers are often required to make substitutions or adopt alternative methods that deviate from the original protocols, potentially impacting the comparability and accuracy of the resulting activity classifications (Rodrigues et al., 2025). Perhaps the two most important considerations when selecting the most appropriate intensity cut-point to utilise is the population of interest and the wear location of choice.

Hip worn and wrist worn cut-points are utilised most consistently to estimate PA and SB for adolescents (Giurgiu et al., 2022). Some of the most popular cut-points for hip worn accelerometery used in the adolescent population (11–18 years) are those by Evenson, Treuth and Romanzini (Migueles et al., 2017; Rodrigues et al., 2025). The Evenson, Catellier, Gill, Ondrak, and McMurray (2008) hip worn cut-points using two accelerometer devices (ActiGraph and Actical). The cut-points produced were 0–47 counts/minute^{-1} (SED), 48–2031 (LPA), 2032–2875 (MPA) and ≥ 2876 (VPA) which were shown to have strong criterion validity when compared to indirect calorimetry. Although the Evenson cut-points have been used to categorise adolescent activity, they were primarily developed for children (5–8 years). Treuth et al. (2004) hip worn cut-points were developed in adolescent girls (13–14 years) using ActiGraphs, producing thresholds of 0–50 counts/30s^{-1} (SED), 51–1499 (LPA), 1500–2600 (MPA), and >2600 (VPA) and showed strong criterion validity against indirect calorimetry. Although the Treuth cut-points were developed for the adolescent age group, they were developed in a female only sample. Romanzini, Petroski, Ohara, Dourado, and Reichert (2014) developed hip worn cut-points for three different accelerometers (ActiGraph GT3X, RT3 and Actical) in adolescents (10–15 years). Cut points of 0–180 counts/15s^{-1} (SED), 181–756 (LPA), 757–1111 (MPA) and ≥1112 (VPA) were created and had almost perfect criterion validity with indirect calorimetry.

Although these hip worn cut-points have been validated within the adolescent population, the known compliance issues of hip worn accelerometers in this population and the growing adoption of wrist worn accelerometers in large scale studies such as the US NHANES and the UK Biobank, has seen a shift in focus toward developing and validating wrist specific cut-points. In adolescents, four of the most commonly used wrist worn cut-points using accelerometers include those developed by Phillips, Chandler and Hildebrand (Migueles et al., 2017; Rodrigues et al., 2025). Phillips et al. (2013) wrist worn (left wrist) cut-points were developed in youth (8–14 years) using the GENEActiv accelerometer. These cut points were < 7 g (SED), 7–19 (LPA), 20–60 (MPA) and >60 (VPA) and showed good criterion validity compared to indirect calorimetry. However, these cut-points were developed in a lab settings and not within a free living environment. Chandler, Brazendale, Beets, and Mealing (2016) developed wrist worn (non-dominant) cut-points for children (8–12 years) in free living conditions for the ActiGraph. These cut points were <305 counts/5s (SED), 306–817 (LPA), 818–1968 (MPA) and ≥ 1969 (VPA) however, these were not validated against a criterion measure. Hildebrand produced wrist worn (non-dominant) cut-points for PA and later SB (Hildebrand, Hansen, Hees, & Ekelund, 2017; Hildebrand, Hees, Hermann, & Ekelund, 2014) for children (7–11 years) and adults (18–65 years) in free-living conditions using ActiGraph and GeneActiv. The Hildebrand cut points are ≤35.6 mg / 1s (SED), ≥35.6 (LPA), ≥201.4 (MPA) and ≥707 (VPA). The cut-point for SB showed good agreement with ActivPAL, a gold standard SB measure and the PA cut-points demonstrated good agreement with indirect calorimetry.

Table 4.2: Cut-points and sleep algorithms for each movement behaviour.

Movement Behaviour	Wear Location	Cut-Point / Algorithm	Thresholds / Criteria	Validation
Physical Activity & Sedentary Behaviour	Hip-worn	Evenson et al. (2008)	0–47 (SED), 48–2031 (LPA), 2032–2875 (MPA), ≥2876 (VPA) (counts/minute^{-1})	Children (5–8 yrs), validated with indirect calorimetry
		Treuth et al. (2004)	0–50 (SED), 51–1499 (LPA), 1500–2600 (MPA), >2600 (VPA) (counts/30s^{-1})	Adolescent girls (13–14 yrs), validated with indirect calorimetry
		Romanzini et al. (2014)	0–180 (SED), 181–756 (LPA), 757–1111 (MPA), ≥1112 (VPA) (counts/15s^{-1})	Adolescents (10–15 yrs), validated with indirect calorimetry
Physical Activity & Sedentary Behaviour	Wrist-worn	Phillips et al. (2013)	<7 (SED), 7–19 (LPA), 20–60 (MPA), >60 (VPA) (g)	Youth (8–14 yrs), validated with indirect calorimetry

		Chandler et al. (2016)	<305 (SED), 306–817 (LPA), 818–1968 (MPA), ≥1969 (VPA) (counts/5s)	Children (8–12 yrs), not validated with criterion
		Hildebrand et al. (2014, 2017)	≤35.6 mg (SED), ≥35.6 (LPA), ≥201.4 (MPA), ≥707 (VPA) (mg / 1s)	Children and adults (18–65 yrs), free-living, validated with indirect calorimetry & ActivPAL
Sleep		Sadeh et al. (1994)	Sleep algorithm that examines movement across an 11-minute window using a weighted summation of activity during the previous epochs, current epoch and following epochs.	Adolescents (10–16 yrs) & adults (20–25 yrs), validated with polysomnography
		Van Hees et al. (2018)	Sleep algorithm that detects sleep period time window using changes in the angle of the arm (angle z)	Adults (60–82 yrs), validated with polysomnography

From each of these wrist worn cut-points the Hildebrand are used most frequently when investigating 24-h MBs in adolescents and have been validated against indirect calorimetry (Rodrigues et al., 2025). Furthermore, one of the greatest strengths of the Hildebrand cut-points is that they utilise the device-agnostic (i.e. non-dependent on accelerometer model) raw acceleration data-driven Euclidian norm minus one (ENMO) metric opposed to proprietary metrics (e.g., counts). In recent years there has been a shift from proprietary metrics to device-agnostic metrics due to their ability to be calculated from any raw accelerometer data regardless of the device type or brand. Additionally, device-agnostic metrics such as ENMO can be created at a low cost due to the increased availability of both raw acceleration data and open source R packages (e.g., GGIR) to process and analyse the data (Fairclough, Rowlands, et al., 2023). However, it is important to acknowledge the Hildebrand cut-point limitations. Trost, Brookes, and Ahmadi (2022) recognised the increased use of wrist worn accelerometer use in youth and the need to independently conduct a validation study, using indirect calorimetry as a criterion measure to simultaneously compare the classification accuracy of seven previously published sets of wrist worn cut-points for youth (14.6 years average). Although all the investigated cut-points did not provide acceptable classification accuracy for estimating time in PA intensities, they highlighted that the Hildebrand cut points 1) misclassified 30% of LPA as SB and 2) underestimated the intensity of MVPA over 75% of the time through misclassifying MPA as SB and underestimating the true intensities of common moderate to vigorous activity types (e.g., walking, basketball and running). Despite these classification issues, Trost et al. (2022) highlighted the need to investigate the Hildebrand cut-points above the other cut-points due to the popularity of researchers using the GGIR accelerometer data processing package in R and the increased use of these particular cut-points in such processing packages.

Sleep algorithms can be used to estimate sleep duration from accelerometer data. Two popular sleep algorithms used for sleep detection in adolescents wearing wrist worn accelerometers are the ones created by Sadeh and Van Hees (Sadeh, Sharkey, & Carskadon, 1994; Van Hees et al., 2018).The Sadeh et al. (1994) algorithm identified wake from sleep by examining movement across an 11-minute window using a weighted summation of activity during the previous epochs, current epoch and following epochs. This algorithm was originally developed in adults (20–25 years) and adolescents (10–16 years) in laboratory settings and showed good validity against polysomnography. This algorithm has been recognised as one of the most popular sleep algorithms to use in adolescents however, the Sadeh algorithm was developed using proprietary count-based data. The Van Hees et al. (2018), algorithm is better suited to researchers working with device-agnostic raw accelerometer data in the GGIR package and has been validated against polysomnography. The Van Hees sleep algorithm does not require sleep diaries as it allows for automated sleep-wake detection. This is particularly useful in the adolescent population where compliance to sleep diary completion is low (Salem, AboElAsrar, Elbarbary, ElHilaly, & Refaat, 2010). The Van Hees algorithm allows for automated sleep-wake detection by using changes in the angle of the arm (angle z) to detect the sleep period time window (SPT-window), which is defined as the window between sleep-onset and waking up after the last sleep episode of the night. This algorithm has been used when investigating 24-h MBs in the adolescent population however, was predominantly developed in adult populations (60–82 years) (Fairclough, Clifford, Brown, & Tyler, 2023).

3.3 Non-wear time

Accelerometers are frequently removed in free living studies where participants are often advised to remove accelerometers during water-based activities (e.g. showering or bathing) and in some studies, when sleeping. This may result in participants forgetting to reattach the monitor for days or parts of days. It is important for researchers to identify these periods of non-wear to ensure time is not misclassified as other low-movement activities (i.e. sleep or SB). This can be done by using a non-wear log diary, where participants are required to log any time they remove and reattach the device, however this is a cumbersome process with low compliance, especially in adolescent populations (Salem et al., 2010). Alternatively, the application of non-wear criteria using algorithms that consider the treatment of consecutive 0 counts within specified time intervals (epochs) recorded by the accelerometer can be used. Several non-wear detection algorithms have been developed including those developed by Troiano and Choi (Migueles et al., 2017). The Troiano et al. (2008) non-wear criteria was developed in children (6–11 years), adolescents (12–19 years) and adults (≥20 years) who wore an accelerometer on their hip. They defined non-wear episodes as intervals of at least 60 consecutive minutes of zero activity counts, with an allowance of 1 to 2 minutes of between 0–100 counts. To validate the Troiano algorithm, the Choi, Liu, Matthews, and Buchowski (2011) algorithm was developed for adults and adolescents who wore an accelerometer on their hip. This algorithm defined non-wear episodes as intervals of at least 90 minutes with consecutive zero counts as non-wear time, allowing for intervals with non-zero counts lasting up to 2 minutes, if no counts were detected during a 30-minute upstream or downstream window from that interval. Both the Troiano and Choi non-wear algorithms are well established within the adolescent population however, these were developed for hip worn accelerometery and utilise the proprietary count metric derived from an unknown algorithm as part of accelerometer software (e.g., ActiLife). Additionally, using the count metric significantly reduces the information present in the underlying raw data (Syed, Morseth, Hopstock, & Horsch, 2020). The Van Hees et al. (2013) algorithm was developed in adults (22–65 years) who wore an accelerometer on the wrist. The algorithm estimates periods of wear and non-wear time using the standard deviation and the value range of each of the three accelerometer axes in 60-minute intervals. If the 60-minute intervals standard deviation were less than 3.0 mg (1 mg = 0.00981 ms) for at least 2 out of the 3 axes, or if the value range was less than 50 mg for at least 2 of the 3 axes then the interval was considered non-wear time. Finally, to allow for overlapping episodes and to accurately highlight the boundaries of non-wear episodes a sliding window of 15 minutes was used.

Although each of the aforementioned non-wear algorithms have been validated, Syed et al. (2020) aimed to build on previous validation studies to examine the performance of algorithms using both epoch and raw acceleration data. They evaluated the Troiano, Choi and Van Hees non-wear algorithms using free-living acceleration data and reported the Van Hees algorithm outperformed each epoch-based algorithm in its ability to detect non-wear time. Additionally, the Van Hees non-wear algorithm is used most frequently in studies investigating 24-h MBs in adolescents and provides raw, device-agnostic acceleration data that can be used and processed in line with other preferred cut points (i.e. Hildebrand cut-points) and sleep algorithms (e.g. van Hees sleep algorithm) (Rodrigues et al., 2025).

3.4 Valid days and valid weeks

It is important to establish the number of hours of wear time that would be representative of an entire day (i.e. valid day) and to set the number of valid days required to be representative of usual habitual behaviour, which is usually 7 full days (i.e. valid week). For studies investigating 24-h MB, the number of hours that constitute a valid day is typically larger than for studies that remove nighttime data. Although data is more reliable when the requirements for a valid day and a valid week are increased, it can potentially lead to a decrease in sample size and subsequent statistical power (Migueles et al., 2017). Across the literature there is substantial variation in what constitutes a valid day of data however, for the 24-h period to be considered valid in adolescent populations, studies have predominantly used the ≥10 waking hours/day (≥600 minutes/day) or the ≥16 hours/day per 24-h period (≥960 minutes/day) criteria (Rodrigues et al., 2025). Additionally, Migueles et al. (2017) conducted a systematic review of accelerometer processing criteria and recommended using ≥10 hours/day (≥600 minutes/day) for a valid day and ≥4 days for a valid week in adolescent populations. For valid week criteria, studies have highlighted the need to include ≥3 valid weekdays and ≥1 valid weekend day for the ≥4 days valid week criteria to be acceptable (Fairclough, Rowlands, et al., 2023) as this will be more representative of typical weekly behaviours which can vary substantially on weekdays and weekends. Although it is recommended to test different criteria to achieve the best compromise between sample size and reliability, researchers may lower the threshold for valid days or weeks when wear compliance is low. However, this should be done cautiously, using sensitivity analyses to ensure that the resulting data still accurately reflect habitual activity patterns.

3.5 Sampling frequency and epoch length

Sampling frequency refers to how many times per second the accelerometer captures raw movement behaviour data for each axis and is measured in Hertz (Hz). Sampling frequency often depends on battery capacity and memory of the device recording the data, with newer devices having the ability to measure movement at a higher frequency over a greater number of days. Generally, it is recommended that researchers use the highest sampling frequency that devices and study protocol (e.g., study duration) allow (Migueles et al., 2017; Rodrigues et al., 2025). For example, a sampling frequency of 100 Hz would capture 100 raw acceleration values per second, per axis as opposed to a 30 Hz capturing 30 raw accelerations. These raw accelerations are often processed to produce activity counts, which are summed within specific time intervals called epochs (e.g., 15s, 30s, 60s). Researchers are required to select the most appropriate epoch length for their research. Aibar et al. (2014) compared the differing effects of 3–60s epoch lengths in adolescents (14.5

years average age) and reported that as epoch length increases estimates of MVPA decrease. Additionally, they reported that smaller epoch lengths increased the resolution of the measure, which increased the time spent in vigorous activity. Due to this they recommend shorter epoch lengths in this population (i.e. 3–15s). Similarly, Altenburg et al. (2021) examined the differing epoch lengths (i.e. 5s, 15s and 60s) on the classification accuracy of free-living SB and MVPA in children (12 years average age) and adolescents (17.4 years average age) by utilising hip worn accelerometers and the Evenson et al. (2008) cut points. They reported a 60s epoch was preferable when aiming to classify SB while a shorter epoch length is required to capture shorter bursts of MVPA. Importantly, they highlight that a longer epoch often results in averaging activity to the middle category. Accelerometers measuring sleep most consistently use a 30s epoch length for classification to ensure it aligns with the conventions used in polysomnography where sleep staging historically uses 30-second windows (Gerstenslager & Slowik, 2020)

For studies examining 24-h MB in adolescents, epoch length is not always reported due to the shift from utilising proprietary count metrics, which need epoch lengths to be defined, to device-agnostic metrics (i.e. ENMO). Instead, the sampling frequency in which raw data is captured is reported most frequently and should be reported anytime raw data is analysed (Rodrigues et al., 2025).

3.6 Axis analysed

Modern accelerometers typically measure movement across three axes (tri-axial), whereas older models may be limited to one (uniaxial) or two (biaxial) axes. This distinction is critical when researchers are utilising cut points that use raw acceleration metrics like the ENMO metric (i.e. Hildebrand cut-points) which require input from all three axes to accurately estimate movement intensity. Specifically, raw triaxial acceleration values are converted into one measure of body acceleration by taking the vector magnitude (VM) from the three axes and then subtracting the value of gravity (*g*) (i.e. $(x^2 + y^2 + z^2)^{½} – 1$).

4. Approaches to analysing 24-hour movement behaviours

Researchers examining accelerometer determined 24-h MB can utilise several analytical approaches within epidemiological studies. Migueles et al. (2022) held a scientific workshop and meeting in Granada to discuss the varying analytical approaches currently utilised in the movement behaviour field, their strengths and limitations, recommendations and future research directions utilising accelerometer data. They highlighted linear regression modelling, isotemporal substitution, functional data analysis, multivariate pattern analysis and machine learning as the most popular analytical methods in determining associations between movement behaviours and health outcomes. While each of these statistical methods have been used extensively in the literature, they are primarily designed for analysing absolute information, rather than relative information, which is crucial for researchers incorporating a 24-h MB paradigm. Although these statistical methods have their advantages in how data is modelled and understood, they do not account for the compositional nature of time-use data (Dumuid et al., 2020).

Compositional data analysis (CoDA) addresses the limitations of statistical methods designed for absolute information by accounting for the relative nature of time-use data. CoDA treats time spent in each behaviour as parts of a finite whole (i.e. 24 hours). The analysis acknowledges that a change in the time spent in one behaviour will change time spent in another and expresses information as a set of log ratios, focusing on the difference between behaviours rather than their raw values (Dumuid et al., 2020). There is one study to date that has explored the use of

CoDA to determine associations between 24-h MBs and health outcomes in adolescents living with T1D. Marshall, Mackintosh, Gregory, and McNarry (2022) aimed to use CoDA to account for the interrelated nature between behaviours and how these behaviours influence cardiovascular health in adolescents (12 years) with T1D. Additionally, Muñoz-Pardeza et al. (2025) utilised CoDA to examine the association between SB, PA and sleep with HbA1c and interstitial glucose in children and adolescents living with T1D. However, there is greater availability of research utilising CoDA to determine the association between 24-h MB and health outcomes in adolescents without chronic conditions (Kuzik et al., 2025). Most researchers utilising CoDA within their studies typically use R software due to the number of established packages available. Additionally, there are a range of resources available aiming to assist researchers in conducting CoDA, including CODAWEB (https://www.compositionaldata.com), which offers training and software specific to CoDA.

5. Overview of rationales for study two

Based on the review of literature, accelerometer processing and analytical decisions were selected to maximise validity and reliability for measuring 24-h MBs in adolescents living with T1D. **Table 4.3** summarises these considerations alongside the rationale for each choice.

Table 4.3: Summary of accelerometer decisions and rationales for study two.

Accelerometer Considerations	Decision	Rationale
Wear location	Non-dominant wrist	Improved compliance, improved data capture of all 24-h MB, no evidence to suggest dominant or non-dominant wrist is more accurate.
Activity cut-points	*Hildebrand 2014, 2017* cut points based on the ENMO (mg per 1s): • SED as < 35.6 • LPA as ≥ 35.6 • MPA as ≥ 201.4 • VPA as ≥ 707	Frequently utilised in 24-h MB adolescent studies, aligns with the research shift in utilising raw device-agnostic data.
Sleep algorithms	*Van Hees 2015* heuristic sleep algorithm based on changes in the arm (angle z)	Sleep-wake detection without sleep diaries aids compliance issues in adolescents, aligns with the research shift in utilising raw device-agnostic data.
Non-wear time	*Van Hees 2013* non-wear algorithm based on the standard deviation and range of each axis.	Frequently utilised in 24-h MB adolescent studies, outperforms epoch-based algorithm to detect non-wear time, aligns with the research shift in utilising raw device-agnostic data.
Valid day	≥10 hours/day (≥600 minutes/day)	Frequently utilised in 24-h MB adolescent studies.
Valid week	≥4 days valid week including ≥3 valid weekdays and ≥1 valid weekend day	More representative of typical weekly behaviours which can vary substantially on weekdays and weekends.
Sampling frequency	80Hz	High frequency that also accommodates for device battery life for 2-weeks of 24-hour wear.
Axis analysed	Three	Required to compute the ENMO metric $(x^2 + y^2 + z^2)^{½} – 1)$

6. Study Two: 24-hour movement behaviour levels using wrist-worn accelerometery in a sample of UK adolescents living with type 1 diabetes: an exploratory study

Licence Note: This section highlights a manuscript prepared for submission as part of this thesis. Pages 127–150 contain the submitted manuscript in its entirety.

Title: 24-hour movement behaviour levels using wrist-worn accelerometery in a sample of UK adolescents living with type 1 diabetes: An exploratory study

Running Title: 24-hour movement behaviours in adolescents living with type 1 diabetes: An exploratory study

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Word Count Main Text: 3397

Word Count Abstract: 287

Conflicts of Interest: M.C. is a consultant for Signfier Medical Technologies, but this activity is not related to the content of this article. The remaining authors declare no conflicts of interest.

Acknowledgements: None.

Abstract

Background: Despite the documented health benefits of physical activity (PA), sedentary behaviour (SB) and sleep on T1D outcomes, there is a notable gap in research examining these behaviours together in adolescents living with type 1 diabetes (T1D). The use of wrist-worn accelerometery has increased over recent years and has demonstrated superior validity for capturing 24-hour activity patterns in adolescents. However, there are limited studies utilising wrist-worn accelerometery to measure movement behaviour levels in adolescents living with T1D.

Objective: This study aimed to objectively assess PA, SB, and sleep using wrist-worn accelerometery in UK adolescents living with T1D.

Methods: A micro-longitudinal study design was employed. Participants aged 11–18 years (n=28) wore wrist-worn ActiGraph GT3X-BT accelerometers for 14 consecutive days. PA, SB and sleep were estimated using the ENMO based Hildebrand cut-points and the van Hees sleep algorithm. Glycaemic control and diabetes-specific Health Related Quality of Life (HRQoL) were self-reported. Welch's t-tests and Spearman's correlations were used to analyse age group differences and associations with glycaemic control and diabetes specific HRQoL.

Results: Adolescents averaged 24.0 ± 24.0 minutes/day of moderate-to-vigorous PA (MVPA), 10.4 ± 1.7 hours/day of SB, and 8.2 ± 0.7 hours/day of sleep. Overall, 7.1% met the MVPA guidelines, and 57.1% met the sleep recommendations. Younger adolescents demonstrated significantly higher SB than older adolescents. No significant association was found between movement behaviours and outcomes.

Conclusion: A large proportion of adolescents with T1D in this study did not meet recommended levels of MVPA or sleep and obtained high levels of daily SB, highlighting the need for tailored interventions. Future studies in this population should adopt standardised, device-agnostic metrics and compositional data analysis in larger, more diverse cohorts to better understand how these behaviours collectively influence diabetes outcomes.

Introduction

Current guidelines recommend adolescents living with T1D should engage in at least 60 minutes of moderate to vigorous physical activity (MVPA) daily due the behaviours crucial role in the management and mitigation of cardiometabolic risk factors (Adolfsson et al., 2018; Colberg et al., 2016). There is growing evidence indicating increased SB levels negatively impacts Hba1c and diabetes distress in adolescents living with T1D however, no specific guidelines for SB exist specific to this population (Huerta-Uribe, Ramirez-Velez, Izquierdo, & Garcia-Hermoso, 2023; Patience et al., 2023; Tilden, Noser, & Jaser, 2023). Similarly, there are no specific sleep guidelines for this population however, the general sleep recommendations of 9–11h/day (11–13 years), 8–10h/day (14–17 years) and 7–9h/day (18–25 years) are recommended (Hirshkowitz et al., 2015). The relationship between sleep duration and HbA1c remains inconsistent, however evidence suggests that increased sleep duration has positive impacts on self-management activities that mediate HbA1c outcomes (Ji, Wang, & Saylor, 2021; Monzon, McDonough, Meltzer, & Patton, 2019). Adolescents living with T1D face additional barriers in obtaining these movement behaviour recommendations due to their diabetes (i.e. fear of hypoglycaemia) and these are thought to increase as adolescents age due to increased autonomy and a reduction in caregiver involvement (Babler & Strickland, 2015).

Despite the documented health benefits of PA, SB and sleep on T1D management and outcomes, there is a notable gap in research on 24-hour movement behaviours (24-h MB) in adolescents living with T1D. All movement behaviours are important in the management of T1D for adolescents and should be promoted with equal importance in the context of the entire day (Dumuid et al., 2020). A holistic 24-h MB approach that considers all behaviours in relation to one another would be appropriate as it would allow adolescents and clinicians to obtain the ‘full picture’ of T1D management requirements and inform health interventions tailored to this group. Wrist-worn accelerometery has become standard in large-scale surveillance initiatives like NHANES and UK Biobank and has demonstrated superior validity for capturing sleep and 24-hour activity patterns in adolescents (Meredith-Jones et al., 2024; Rosenberger et al., 2019). However, there are limited studies utilising wrist-worn accelerometery to measure PA, SB and sleep levels in adolescents living with T1D (Marlow, King, Trost, Weaver, & Smart, 2023).

The primary aim of this study was to objectively assess PA, SB and sleep in a sample of UK adolescents living with T1D using wrist-worn accelerometery. Secondary aims were to examine age-related differences in movement behaviours and explore preliminary associations between movement behaviours, glycaemic control (HbA1c), and health-related quality of life (HRQoL).

Study Design and Setting

Participants

Participants were eligible for this micro-longitudinal study if they were aged 11–18 years, were diagnosed with T1D, currently lived in the UK, spoke English, had no mobility related issues or required walking aids and had not been diagnosed with a sleep disorder.

Study Procedure

Recruitment and data collection occurred over a 6-month period between March 2023 and August 2023. Recruitment of participants was completed remotely through online methods (e.g., Twitter, Instagram, T1D Facebook groups) and word of mouth. Recruitment materials included a video of the lead researcher describing the research, aiming to engage this typically harder to reach population more successfully and infographics (Culshaw, 2020).

The recruitment materials made available online directed participants to a baseline questionnaire to initially assess eligibility and consent. For adolescents aged 11–15 years, an online verbal consent meeting was conducted with the adolescent and their parent/caregiver. For adolescents aged 16–18 years, written consent was obtained online. Once consent was obtained, participants completed a 5–10-minute baseline questionnaire. This questionnaire asked for contact (name, email and home address), demographic (age, sex, ethnicity), and diabetes specific information (diabetes duration, HbA1c (%), type of insulin, insulin modality, times per day insulin was administered, blood glucose measurement type). Additionally, participants completed the PedsQoL 3.2 Diabetes Module (Varni et al., 2018).

Following completion of the baseline questionnaire, research packs were posted to participants home address. These research packs included an accelerometer to wear for 2-weeks, instructions on how to wear the device and return research materials. Additionally, the research packs included non-wear diaries to support compliance monitoring and help contextualise unusual activity patterns by cross-checking against non-wear output. Researchers contacted participants upon questionnaire completion, once research packs had been sent, 1-week post wear, 2-weeks post wear and finally to inform them the accelerometer had returned back to the research centre.

Study Outcomes

The variables of interest for this study were MVPA, SB and sleep duration. The UK Physical Activity Guidelines of ≥60 min/day of MVPA and the National Sleep Foundation (NSF) sleep duration of 9–11h/day (11–13 years), 8–10h/day (14–17 years) or 7–9h/day (18–25 years) were utilised to determine if adolescents had met recommendations (Hirshkowitz et al., 2015; UK Chief Medical Officers, 2019).

HRQoL was measured using the validated Paediatric Quality of Life (PedsQL) 3.2 Diabetes Module for adolescents with T1D. This 33-item measures diabetes-specific HRQoL and consists of five-point likert scale (never, almost never, sometimes, often and almost always) measuring diabetes symptoms (15 items), treatment barriers (5 items), treatment adherence (6 items), worry (3 items), and communication (4 items). This measure is reverse scored and linearly transformed to a 0–100 scale (0=100, 1=75, 2=50, 3=25, 4=0), with lower scores indicating more diabetes symptoms and management problems and ultimately a poorer diabetes-specific HRQoL.

Participants were asked to report their HbA1c value measured at their most recent diabetes appointment, which measures the average level of blood glucose over the past 2–3 months to indicate long-term glycaemic control. The National Institute for Health and Care Excellence recommends an HbA1c level of ≤6.5% (48mmol/mol) to minimise the risk of long-term complications (National Institute for Health and Care Excellence (NICE). 2015).

Accelerometer

PA, SB and sleep were measured using ActiGraph GT3X-BT tri-axial accelerometers (ActiGraph, Pensacola, FL, USA) which have been used to provide an objective measure of each behaviour (Tapia-Serrano et al., 2022; Wilhite et al., 2022). The participants wore the accelerometer on their non-dominant wrist to improve participants compliance to wear protocols and ultimately increase the reliability of the data (Doherty et al., 2017). Additionally, wrist-worn attachment sites allow for improved capturing of data over the 24-hour day (Rosenberger et al., 2019). Participants were asked to wear the device for 24 hours/day for 14 consecutive days, except when completing water-based activities (e.g., bathing, swimming etc). Accelerometers were initialised to collect data on three axes at a sampling rate of 80Hz at midnight on day 1.

Accelerometer Data Reduction

Accelerometer data were downloaded using ActiLife software version 3.2 (ActiGraph Corp., Pensacola, FL, USA), saved as raw GT3x files that were then read into R (http://cran.r- project.org) and summarised with package GGIR (R package for accelerometery) (Migueles, Rowlands, Huber, Sabia, & van Hees, 2019) version 2024.04.2+764 using the Euclidean norm minus one (ENMO) metric expressed in milligravitational units (*mg)*. Non-wear time was detected depending on statistics from a rolling time window. A step-in time was classified as non-wear if both the range of accelerations (i.e., maximum value minus minimum value) was less than 50*mg* and if the standard deviation of the accelerations was less than accelerometer brand specific reference values for at least two out of the three axes, which for most brands is 13*mg (Van Hees et al., 2013).* The valid day criteria used in R was ≥10 hours or ≥ 600 min·d−1 and a valid week was defined as ≥4 valid days across the two weeks of wear (including one weekend day) (Fairclough, Rowlands, et al., 2023). To be included in the analysis, participants needed to have at least one valid week of data, across the two-week monitoring period. Data sets not meeting this criterion were removed from analysis. Average acceleration values of ≤35.6 mg/1s, ≥201.4 and ≥707 were used to calculate SB, MPA and VPA respectively (Hildebrand, Hansen, Hees, & Ekelund, 2017; Hildebrand, Hees, Hermann, & Ekelund, 2014). To estimate sleep duration, a polysomnography validated accelerometer algorithm (Van Hees et al., 2018). This algorithm allows for automated sleep-wake detection without needing sleep diaries, which is particularly beneficial in adolescent populations where compliance to sleep diary completion is low (Salem, AboElAsrar, Elbarbary, ElHilaly, & Refaat, 2010). It detects sleep by using changes in the angle of the arm (angle z) to detect the sleep period time window (SPT-window), which is defined as the window between sleep-onset and waking up after the last sleep episode of the night.

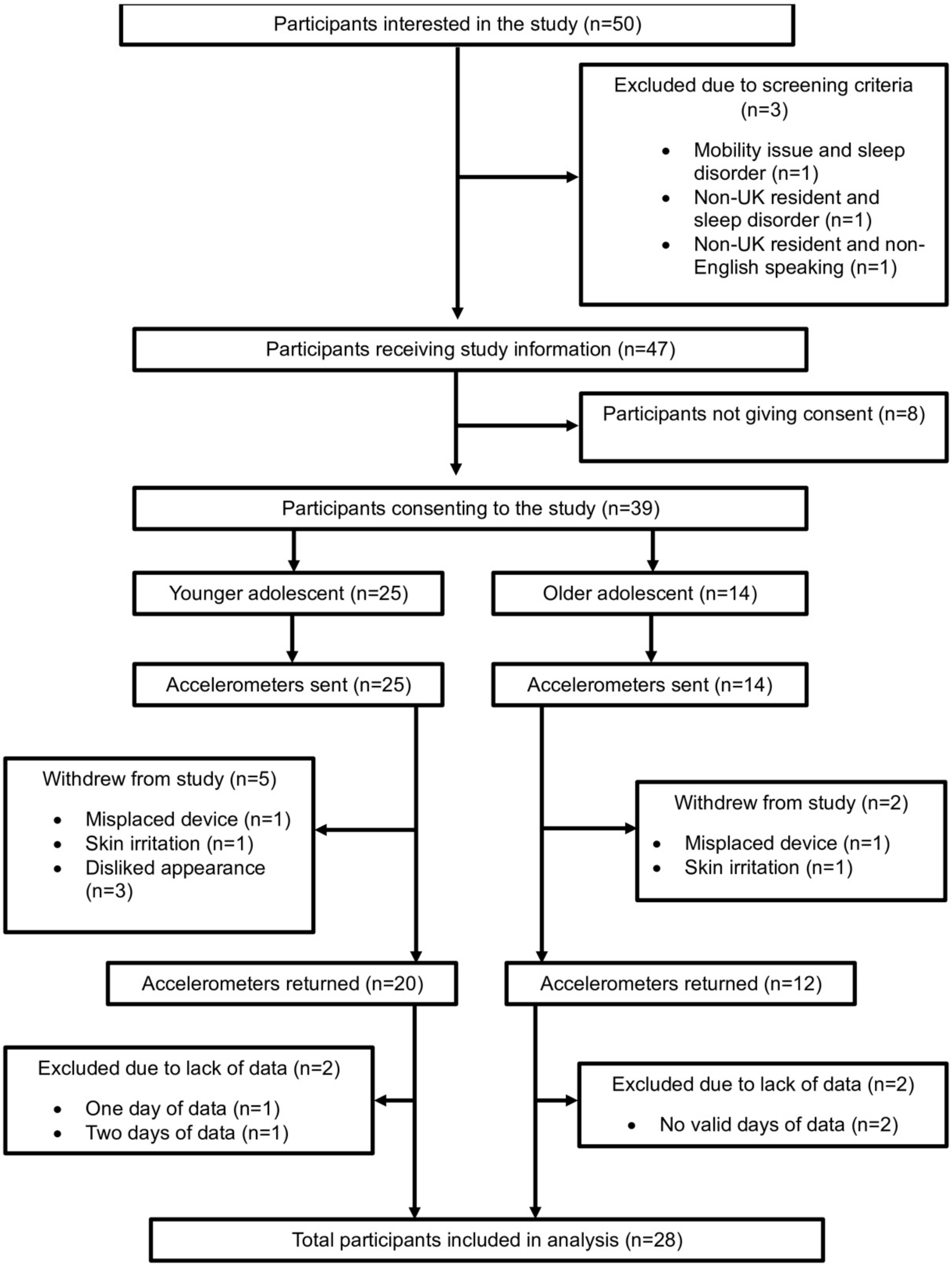
Statistical Analysis

Data were analysed using SPSS version 29.0.2.0. There was a low proportion of missing data (<20%) across some questionnaire variables. To assess the nature of the missing data, Little's MCAR test was conducted using SPSS, which indicated that the data were Missing Completely at Random ($p > 0.05$) (Little, 1988). This suggests that the pattern of missingness was not dependent on participants' characteristics (e.g., age, gender), supporting the use of mean imputation for handling missing values. To test for differences between groups, normality of variables between younger (11–15 years) and older adolescents (16–18 years) was assessed using Shapiro-Wilk tests due to the small sample size and histograms and Q-Q plots were examined visually. Additionally, homogeneity of variance was assessed using the Levene's test. Welchs t-tests were utilised for sleep, SB, HRQoL total score, diabetes management and diabetes symptoms scores and Whitney U test was utilised for MVPA and HbA1c due to the non-normal distribution. For correlations between movement behaviours and diabetes outcomes, normality of all scale variables was assessed numerically using Shapiro-Wilk tests and linearity between variables were assessed through R^2 values and visually using scatter plots. Due to violations of normality and linearity of variables, alongside the small sample size (n=28) Spearman's rank correlation was utilised.

Results

Overall, 50 participants were interested in the study. After screening and communication of study requirements 39 participants consented to take part and accelerometers were sent to each participant. Thirty-two accelerometers were returned and 28 participants had sufficient data to be included in the analysis (**Figure 1**).

Figure 1: Flow chart of participants included in analysis.



Participants demographic information and summary statistics for movement behaviours, HbA1c and HRQoL are summarised in **Table 1**. Participants had a mean age of 14.4 ± 1.8 years and an average diabetes duration of 4.9 ± 4.0 years. The sample was composed of 46.4% males and 53.6% females who predominantly described their ethnic background as White British (92.9%). Participants monitored their blood glucose levels predominantly through continuous glucose monitors (CGMs) (75%) and delivered insulin by pump (64.3%). The average HbA1c of the group was 7.6 ± 1.5 %, indicating good glycaemic control and the average HRQoL total score was 61.2 ± 13.0 indicating good overall quality of life (higher score indicates better quality of life). The sample was composed of 64.3% younger adolescents (11–15 years) and 35.7% older adolescents (≥16–18 years).

Table 1: Participant characteristics for the full sample (n=28). Frequency data is given as number and percentage; descriptive data is given as mean ± standard deviation.

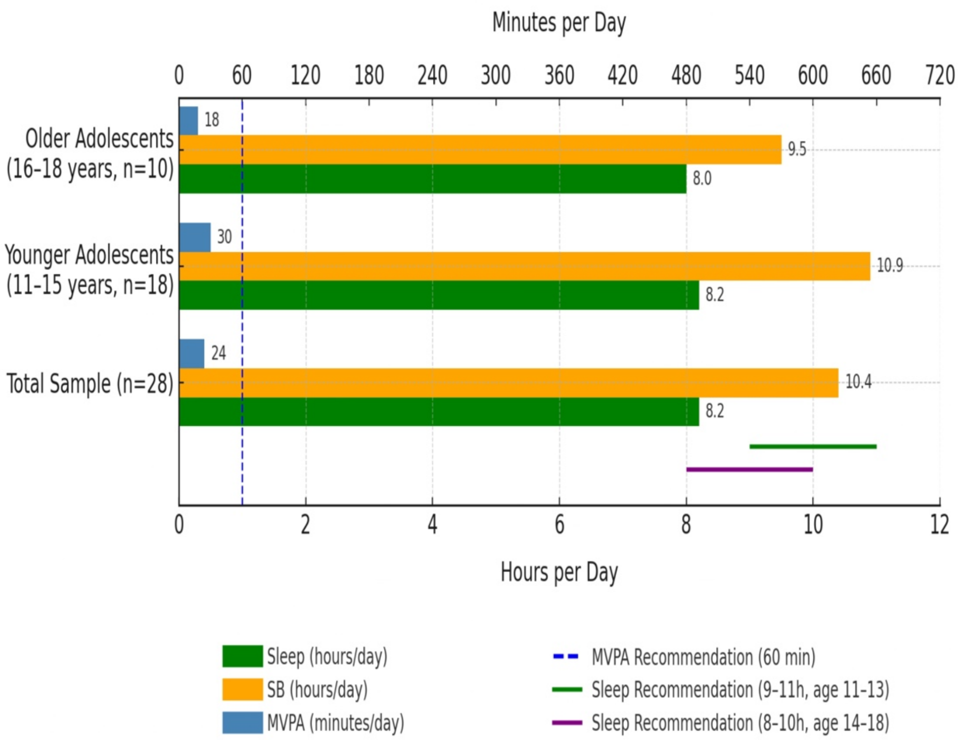
Characteristic	**Full Sample (n=28)**	**Younger Adolescent (n=18)**	**Older Adolescent (n=10)**
Sex (N, %)			
Female	15 (53.6)	7 (38.9)	8 (80)
Male	13 (46.4)	11 (61.1)	2 (20)
Ethnicity (N, %)			
White British	26 (92.9)	16 (88.9)	10 (100)
Jewish	1 (3.6)	1 (5.6)	-
Mixed of multiple ethnic groups	1 (3.6)	1 (5.6)	-
Insulin Delivery (N, %)			
Pen	10 (35.7)	4 (22.2)	6 (60)

Pump	18 (64.3)	14 (77.8)	4 (40)
Blood Glucose Measurement Method (N, %)			
CGM	21 (75)	13 (72.2)	8 (80)
Flash glucose monitor	4 (14.3)	3 (16.7)	1 (10)
Finger Prick	3 (10.7)	2 (11.1)	1 (10)
Age (yrs, M, SD)	14.4 ± 1.8	13.2 ± 0.9	16.6 ± 0.7
Diabetes Duration (yrs, M, SD)	4.9 ± 4.0	4.6 ± 4.1	5.2 ± 4.0
HbA_{1c} (%, M, SD)	7.6 ± 1.5	7.4 ± 1.0	8.0 ± 2.0
Diabetes Symptoms (M, SD)	53.5 ± 11.8	55.6 ± 7.8	49.8 ± 16. 7
Diabetes Management (M, SD)	67.6 ± 16.9	73.6 ± 14.7*	56.8 ± 15.9*
HRQOL (M, SD)	61.2 ± 13.0	65.4 ± 9.8*	53.6 ± 14.9*
Sleep (hours/day, M, SD)	8.2 ± 0.7	8.2 ± 0.8	8.0 ± 0.6
SB (hours/day, M, SD)	10.4 ± 1.7	10.9 ± 1.5*	9.5 ± 1.7*
MVPA (min·day, M, SD)	24 ± 24	30 ± 30	18 ± 12
Meeting Sleep Recommendations (N, %)	16 (57.1)	9 (56.3)	7 (43.7)
Meeting MVPA Recommendations (N, %)	2 (7.1)	2 (11.1)	0 (0)
Valid Days (M, SD)	8.8 ± 2.0	8.6 ± 1.8	9.2 ± 2.4

* $p < 0.05$

On average, adolescents in this sample spent most of the 24-hour day participating in 10.4 ± 1.7 hours/day of SB. Their average sleep time was 8.2 ± 0.7 hours/day, and they spent 24 ± 24 minutes a day of MVPA. Sixteen (57.1%) participants met the sleep recommendations for their age group as recommended by the National Sleep Foundation (n=9 younger; n=7 older). Two (7.1%) participants met the 60 min/day of MVPA recommendations outlined by the UK MVPA guidelines (n=2 younger n=0 older) (**Figure 2**).

Figure 2: Movement behaviour levels compared to the movement behaviour guidelines.



Significant differences between younger and older adolescents were found for diabetes management scores (t = 2.760, p = 0.013), overall HRQoL score (t = 2.245, p = 0.042) and SB levels (t = 2.150, p = 0.047) between younger and older adolescents. Bivariate correlations highlighted negative relationships between HbA1c, sleep, MVPA and SB and positive relationships between HRQoL, Sleep, MVPA and SB. However, none of these were statistically significant ($p > 0.05$) (**Table 2).**

Table 2: Correlation coefficients between variables for the whole sample (n=28).

Spearman's rho coefficient (p)	1	2	3	4	5	6	7	8	9	10
1. Age (yrs)	1.000									
2. Diabetes Duration (yrs)	.087	1.000								
3. HbA1c (%)	.257	-.084	1.000							
4. Insulin administration/day	.423*	-.268	.275	1.000						
5. Diabetes Symptoms	-.144	-.280	-.397*	-.014	1.000					
6. Diabetes Management	-.438*	-.114	-.292	-.244	.541**	1.000				
7. HRQOL Total Score	-.357	-.196	-.314	-.179	.771**	.944**	1.000			
8. Sleep (hour·day)	-.320	.308	-.054	-.307	.025	.119	.114	1.000		
9. SB (hour·day)	-.195	-.201	-.088	.200	.232	.262	.274	-.307	1.000	
10. MVPA (hour·day)	-.219	.080	-.328	-.299	.182	.151	.144	.156	-.474*	1.000

* are significant at the 0.05 level (2-tailed); ** are significant at the 0.01 level (2-tailed).

Discussion

This studies primary aim was to explore the PA, SB and sleep levels in a sample of UK adolescents living with T1D using wrist-worn accelerometery. Adolescents in this sample performed an average of 24 minutes/day of MVPA, 10 hours/day of SB, 8h/day of sleep. Wu et al. (2021) investigated the MVPA levels of adolescents (14.02 years, n=48) with T1D using wGT3x-BT Actigraph accelerometers worn on the non-dominant wrist for 7 days. They reported 53.19 minutes/day of MVPA however, this was calculated using Evenson cut-points which were originally developed for waist worn estimates of PA. SB levels were not reported in this study. Marlow et al. (2023) utilised GT9X accelerometers in adolescents (14.8 years, n=37) with T1D worn on the non-dominant wrist for 24-hours a day over 7-days and reported 44 minutes/day of MVPA and 11.02 hours/day of sedentary time. These intensity estimates were derived using machine learning where a classification algorithm originally developed to derive intensity estimates in children was used. Muñoz-Pardeza et al. (2025) investigated the MVPA and SB levels of adolescents (12.7 years, n=83) using GENEactive accelerometers on the non-dominant wrist over a 9-day period and reported MVPA levels of 33.06 min/day and 10.2 hours/day of SED. These levels are more aligned to the levels reported in our study which might be explained by the use of the Hildebrand cut-points to derive intensity estimates.

Wrist-worn accelerometery is commonly used in research due to its strong validity for assessing sleep duration and quality in adolescents (Meredith-Jones et al., 2024; Morgenthaler et al., 2007). Studies have reported sleep duration ranges between 6.5 hours to 7.4 hours in adolescents living with T1D (Babinski, Duperval, Altenor, & von Oettingen, 2023; Frye, Perfect, & Silva, 2019; Griggs, Redeker, Jeon, & Grey, 2020; Patel et al., 2018; Perfect et al., 2012). However, these studies highlight utilising Actigraph software to derive sleep-based estimates without disclosing the specific sleep algorithm used which decreases standardisation across the literature and creates difficulties in interpreting results. Sleep algorithms that have been used in adolescents living with T1D include the Galland, Kennedy, Mitchell, and Taylor (2012) algorithm, Sadeh, Sharkey, and Carskadon (1994) algorithm and Van Hees et al. (2018) algorithm reporting 7.9 hours/day, 7.02

hours/day and 7.57 hours/day, respectively (Macaulay et al., 2020; Marlow et al., 2023; Wu et al., 2022). Although there are a number of sleep algorithms utilised across the literature, a study conducted by Meredith-Jones et al. (2024) aiming to determine the performance of 11 sleep algorithms in relation to overnight polysomnography (PSG) in children and adolescents (8-16 years) reported the van Hees algorithm obtained the greatest specificity and accuracy. Additionally, the van Hees sleep algorithm does not require a sleep diary which is particularly useful given compliance to sleep diary completion is low in the adolescent population (Salem et al., 2010).

The preliminary findings of this study indicate that younger adolescents with T1D engage in higher levels of MVPA, sleep, and SB than their older counterparts, although only the difference in SB reached statistical significance. The lower levels of MVPA observed in older adolescents align with previous research in the general population, where total PA tends to decline during adolescence, and MVPA drops sharply between the ages of 9 and 15 years (Dumith, Gigante, Domingues, & Kohl III, 2011; Nader, Bradley, Houts, McRitchie, & O'Brien, 2008). Similarly, lower durations of sleep in older adolescents has been reported in the literature, which is attributed to a "perfect storm" of bioregulatory (homeostatic sleep and circadian time systems) and psychosocial (bedtime autonomy, academic pressure, screen time and social networking) pressures that become more prevalent with age (Carskadon, 2011). The decreasing trend in PA and sleep is further intensified in adolescents with T1D as increasing age typically brings greater autonomy in diabetes self-management (Huerta-Uribe, Hormazábal-Aguayo, Izquierdo, & Garcia-Hermoso, 2023; Ji et al., 2021). While younger adolescents often benefit from close caregiver involvement, older adolescents must independently manage the complexities of glucose regulation (Babler & Strickland, 2015). This negatively impacts the willingness of T1D adolescents engaging in and profiting from the health benefits of movement behaviours (Bowen, Holtman, Reich, & Simon, 2024; Custy et al., 2024). The finding of higher SB in younger adolescents does not align to previous research, which reports an age-related increase in various forms of SB (Kontostoli et al., 2021). However, variability across socio-demographic subgroups and the context of SB remain underexplored. Given this study captured only objective sedentary time, future research should incorporate contextual measures to better understand age-related patterns in adolescents with T1D. No significant associations were found between movement behaviours and HbA1c or HRQoL, however trends suggested that greater sleep and MVPA were linked to improved outcomes, which aligns with previous research (Patience et al., 2023). In contrast, the observed positive trend between SB and clinical outcomes contradicts existing evidence (Patience et al., 2023). This unexpected finding might be explained by the context in which SB is undertaken. For example, homework activities in adolescents living with T1D is associated with the conscientiousness personality trait which has been found to be related to positive self-management behaviours and thus glycaemic control (Rassart et al., 2018).

A major strength of this study was the use of wrist-worn accelerometers and raw data processing methods aligned with a 24-h MB framework. Intensity estimates were derived using Hildebrand cut-points, which are widely used in adolescent 24h-MB research and validated against indirect calorimetry (Rodrigues et al., 2025). These cut-points utilise the device-agnostic Euclidean Norm Minus One (ENMO) metric, enabling consistent analysis across accelerometer brands and reducing variability introduced by proprietary count-based methods. The increasing use of raw acceleration data and open-source tools such as the GGIR R package supports more transparent, cost-effective, and standardised processing across studies (Fairclough, Rowlands, et al., 2023). For sleep estimation, the van Hees algorithm was applied. This algorithm is validated against polysomnography and offers automated sleep-wake detection without requiring sleep diaries, which is an important advantage given low diary compliance in adolescents (Salem et al., 2010). Additionally, this sleep algorithm has been successfully applied in adolescent 24h-MB research (Fairclough, Clifford, Brown, & Tyler, 2023).

Although using wrist-worn research grade accelerometers increases compliance in the adolescent population and creates easier analysis of 24-h MBs, there was still a proportion of adolescents who withdrew from the study due to device wear (Scott et al., 2017). In the general adolescent population, compliance with wearing research-grade accelerometers is challenging due to comfort, size of the device, visibility, interference with daily activities and social image (Grimes et al., 2025). These challenges are compounded in adolescents living with T1D, due to the burden of technology already associated with T1D. Morrow, Kirk, Muirhead, and Lennon (2023) identified ‘social acceptance and identity’ as a key theme, where adolescents living with T1D expressed discomfort with device visibility and the emotional toll of managing their condition in public. Adolescents described situations in which they actively concealed device use to avoid unwanted attention. This suggests that introducing an additional wearable device, such as a research-grade accelerometer, could exacerbate social anxiety or device fatigue. Despite the specific challenges of using research grade wearables in this population, there are currently no studies investigating the most appropriate wear placement to reduce potential compliance barriers and ensure sufficient data collection. Another limitation of this study was the small homogenic sample, which was predominantly white British and had a lack of racial /ethnic diversity present. The sample had HbA1c levels that indicated good glucose control and good quality of life scores. This might be linked to the high proportion of the sample utilising diabetes technologies to monitor blood glucose levels and administer insulin which has been shown to improve HbA1c and psychosocial outcomes (Tauschmann et al., 2025).

To strengthen understanding of how 24-h MBs relate to clinical outcomes such as HbA1c and HRQoL, future research should involve larger and more diverse cohorts. Stratification by age, glycaemic control, and diabetes technology use is recommended. Future studies might employ compositional data analysis (CoDA) to account for the co-dependent nature of these time-use behaviours, enabling more accurate and meaningful interpretation of how the balance between PA, SB, and sleep influences health in adolescents with T1D (Dumuid et al., 2020). To do this it is important for the wrist-worn accelerometer processing decisions to be standardised and consistent with regards to this population. Adopting device-agnostic metrics such as ENMO and clearly reporting cut-points and sleep algorithms will enhance comparability across studies and strengthen the interpretation of 24-h MB data in adolescents with T1D.

Conclusion

A substantial proportion of adolescents living with T1D in this study were not meeting the recommended movement behaviour levels for optimal health. While movement behaviour barriers are common during adolescence, they are further amplified in those with T1D and amplified again due to the autonomy associated with increased age. To better understand how 24-h MB interact and influence key diabetes outcomes, future research should involve larger, more diverse samples and employ standardised, transparent accelerometer data processing decision and analysis consistent with the 24-h MB framework.

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7. Chapter summary

Chapter four summarised the micro-longitudinal study completed for this thesis aiming to objectively assess PA, SB, and sleep using wrist-worn accelerometery in UK adolescents living with T1D. The findings indicated that a large proportion of adolescents with T1D did not meet recommended levels of MVPA or sleep and obtained high levels of daily SB, highlighting the need for tailored and context specific interventions. To facilitate understanding of how such an intervention might be supported, it is necessary to understand how adolescents living with T1D perceive and prioritise these behaviours within a day. Therefore, the next chapter examines adolescents lived experience, beliefs and perceptions of 24-h MBs and how these interact with diabetes self-management.

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Chapter 5 - Study Three, Qualitative Exploration of 24-h Movement Behaviours

1. Chapter overview

This aim of this chapter is to present the third study of the PhD: a qualitative study using semi-structured interviews to investigate the perceptions of adolescents living with T1Ds towards 24-h MBs. Initially, a comprehensive overview of the key and current qualitative 24-h MB research is explored followed by a discussion of key epistemological and ontological considerations for study three. Additionally, the methodological considerations for study three (i.e., data collection, transcription and analysis considerations, reflexivity, positionality and the role of the researcher) will be discussed in greater detail than what was permitted in the published article due to the specified journal requirements (i.e. word count). The chapter will finish with the second study conducted for this thesis which has been published in the *International Journal of Environmental Research and Public Health.*

2. Overview of qualitative research paradigm

Qualitative research is a form of investigation aiming to delve deeper, explore and understand human experience, behaviours, emotions and perceptions. One of the greatest strengths of qualitative research is its ability to explore complex processes and human behaviours that can be challenging to quantify otherwise, by allowing the participants themselves to describe and explain the “how” “what” and “why” of their reality and knowledge (Cleland, 2017; Moser & Korstjens, 2017). A qualitative approach prioritises the context within which individuals interpret their experiences and construct meaning. It focuses on understanding participants lives as they experience them which is particularly important for adolescents living with T1D who have unique experiences (Leung, Tang, Lim, Laffel, & Amed, 2021).

3. Qualitative 24-h MB research in adolescents living with T1D

To the researcher’s knowledge, there are currently no qualitative studies investigating adolescents living with T1D perceptions towards a 24-h MB approach or how each behaviour might be perceived to affect one another and important T1D outcomes. While qualitative studies exist examining PA and sleep individually, no qualitative research has investigated perceptions of SB specifically. This could be due to several factors including perceived lack of urgency in comparison to the other behaviours (i.e., PA is a cornerstone of T1D management with SB often viewed as secondary, especially in relation to blood glucose management where blood glucose excursions are less drastic in relation to SB), limited awareness of the impact of SB on adolescent T1D health outcomes and potential measurement challenges (i.e., defining SB accurately enough to discuss with adolescents in interviews ensuring the behaviour is not viewed as simply ‘inactivity’).

Out of the three movement behaviours, qualitative studies investigating the perceptions of PA in adolescents living with T1D have been investigated most frequently. A recent systematic review conducted by Dash, Goyder, and Quirk (2020) investigated the factors affecting participation of children and adolescents with T1D. Study participants included adolescents living with T1D, family members, teachers, coaches and healthcare professionals. They identified 14 studies and reported the main factors affecting PA participation for adolescents living with T1D were 1) individual characteristics (e.g., adolescent intrinsic motivation); 2) blood glucose monitoring requirements (e.g., insulin/carbohydrate intake and fear of hypoglycaemia); 3) support systems (e.g., friends, family, role models, teachers); 4) education and knowledge (e.g. advice regarding glucose excursions from healthcare professionals) and 5) communication between stakeholders (e.g., allows for planning of glucose intake and potential limitations present for adolescents). Overall, children and adolescents living with T1D generally viewed PA positively by frequently discussing the activity in relation to enjoyment and associated health benefits. However, they felt the constant blood glucose monitoring requirements before, during and after activity was a major barrier. The greatest facilitator of PA discussed by adolescents living with T1D was the social support received by friends, family and teachers (e.g., co-participation, logistical support of travelling to and from activities and costs associated with activities). Family members felt the greatest barrier to adolescents PA was their own PA anxieties, which was especially heightened if their child had difficulties regulating their own blood glucose without support. They believed supporting their child in PA facilitated participation and having correct PA education/advice for those within their child's immediate environment would relieve their own PA anxieties. Teachers felt adolescents with T1D would be more likely to participate in PA if teachers adopted positive approaches, were flexible in their approach to suit needs of adolescents and were transparent communicators with important stakeholders involved in the T1D adolescent environment. Finally, healthcare professionals recognised blood glucose requirements being the main barrier to PA for adolescents living with T1D. Interestingly, healthcare professionals believed caregivers to be overprotective of their child which presented a barrier to PA participation. Since this systematic review, Fried et al. (2021) conducted focus groups with adolescents, young adults and parents to investigate the challenges experienced by these populations when physically active and reported similar results. Data was analysed via content analysis and challenges associated with PA included: 1) unpredictability of blood glucose (i.e., varied outcomes depending on activity type); 2) knowledge (i.e., lack of knowledge from community with specificity to teachers and peers) and 3) trust (i.e., trust that others surrounding adolescents have sufficient knowledge and a positive attitude towards T1D) and stigma (i.e., not being defined by their T1D). For parents the main challenge was specifically involving unpredictability and trust (i.e., parental trust towards their child's ability to self-manage their condition).

Qualitative studies investigating the relationship between sleep and T1D have gained traction over recent years. Bergner et al. (2018) aimed to identify barriers, facilitators, and consequences of obtaining sufficient sleep in adolescents (15.6 years) with T1D. Semi-structured interviews were conducted with adolescents and caregivers and the thematic analysis conducted highlighted specific diabetes barriers and non-diabetes specific barriers. Non-diabetes specific barriers included use of electronics before bed, homework or school related activities, sports, mood and external factors (e.g., outside noise, family members). Diabetes related sleep disruptions included: 1) frequent awakenings due to blood glucose fluctuations, urinating and/or hydration needs and 2) delayed bedtimes due to diabetes management activities. Adolescents that used diabetes technology also highlighted the alarms associated with their diabetes technology frequently woke them and the technology itself was uncomfortable to sleep with. When caregivers were asked about barriers to sleep, they only discussed the diabetes related sleep disruptions highlighted by adolescents. Additionally, when caregivers were asked about potential facilitators of sleep they discussed the use of early bedtimes, technology (e.g., playing music), sleep aids and limited distractions before bed (e.g., no electronics). Although most adolescents could not identify facilitators to sleep few highlighted sleep aids and technology as useful. Importantly, both caregiver and adolescents understood that sleep disruptions caused them to feel lethargic and tired the next day which had negative consequences for their diabetes management activities.

Similarly, Bowen, Holtman, Reich, and Simon (2024) aimed to identify facilitators and barriers to good sleep health in adolescents with T1D (15.8 years). Semi-structured interviews were conducted with parent-adolescent dyads and thematic analysis was conducted. Generally, dyads recognised the importance of sleep and noted a bi-directional behaviour between the behaviour and self-management. The most identified barrier to sleep was overnight diabetes management activities (e.g., treating a high or a low), which affected both the adolescent and the caregiver. Other barriers to sleep included electronic use, anxiety (diabetes specific and general), snacking late at night or socialising at sleepovers, which impacted glucose control, and school (e.g., early school starts, excessive homework and extracurricular activities). Facilitators to better sleep health included a comfortable environment (e.g., dark, cool, weighted blanket, quiet/white noise), a consistent schedule, sleep aids (e.g., melatonin), diabetes technology (e.g., CGM and closed loop), prioritising sleep, stress release (e.g., music, candles and meditation). Notably, one of the facilitators to sleep identified was exercise.

Macaulay, Boucher, Yogarajah, Galland, and Wheeler (2020) focused primarily on the sleep of parents who have caring responsibilities for adolescents with T1D. They reported a range of diabetes-related factors affecting parents sleep (e.g., fear of hypoglycaemia, glucose monitoring, daytime snacking or exercise) which then had a subsequent impact on other variables such as diabetes management, reduced exercise and relationships. Parents also highlighted diabetes technology as both a barrier and facilitator to sleep.

Within these aforementioned qualitative studies, each outlined specific data collection and analytical decisions that are important to consider in relation to the findings. The next section of this chapter discusses these key considerations and how they impact qualitative findings and interpretation.

4. Data collection and analytical decisions

Researchers undertaking qualitative research must consider important data collection and analytical decisions. **Table 5.1** highlights the key data collection considerations that require evaluation to ensure the experiences of adolescents living with T1Ds perspectives and experiences of 24-h MBs is captured accurately for study three.

Table 5.1: Key qualitative considerations.

Qualitative Considerations	Description
Research paradigm	Influenced by concepts of epistemology (knowledge) and ontology (reality). Designed to give a "world view" that informs methods and methodologies.
Qualitative data collection method	Data collection methods allowing the participant themselves to describe and explain the "how" "what" and "why" of their reality and knowledge.
Transcription	Transformation of spoken word or recorded audio into written form.
Analytical approach	Analytical approaches to identify patterns and themes.
Positionality and role of the researcher	A person's overall view of the world and how they might conduct research.
Reflexivity	Researchers constantly assessing, recognising and disclosing themselves within their research in a bid to better understand their role and influence on the research.

5. Research paradigm

Epistemology and ontology are the two main concepts underpinning research philosophy. Ontology is the study of existence and beliefs about reality as we know it and epistemology is the theory of *how* knowledge is constructed (Scotland, 2012). Epistemology and ontology are intertwined and influence research paradigms. These paradigms are designed to give "world views" that inform methods and methodologies (Devers, 1999; Scotland, 2012). There are several research paradigms posited and utilised within different research fields. Three research paradigms that reflect core philosophical assumptions are positivism, interpretivism and pragmatism.

Positivism argues that reality exists independent of humans and knowledge is created through experimentation and empirical evidence. The positivism research paradigm has dominated research within basic and clinical science and has been used consistently throughout the years to collect mostly quantitative data to advance science (Schrag, 1992). However, this paradigm's ability to study individuals and social phenomena has been widely criticised (Gage, 1989; Gall, Borg, & Gall, 1996; Grix, 2018; Richards, 2003). Interpretivism posits that there are multiple socially constructed realities and is created as opposed to discovered. An interpretive methodology aims to investigate social phenomena in the context of the individual aiming to understand through the lens of the participant rather than the researcher (Cohen, Manion, & Morrison, 2002). Data is mostly qualitative, and analysis of data is inductive in nature, utilising methods such as, open ended interviews (structured and semi-structured), focus groups, observations, diaries or journals etc. The pragmatic paradigm is centred around the solving of practical problems present in the real world through investigation (Biesta & Burbules, 2003; Yvonne Feilzer, 2010).

In pragmatism, reality is understood based on its usefulness in particular contexts (Allemang, Sitter, & Dimitropoulos, 2022). Pragmatic methodologies aim to address practical issues that arise directly from specific communities by utilising mixed methods and action-orientated inquiry (Hothersall, 2019; Johnson & Onwuegbuzie, 2004).

Research paradigms should be selected based on the suitability to the phenomena the researcher wishes to investigate and will determine the methods and methodologies used (Rehman & Alharthi, 2016). Study three was informed primarily by interpretivism, aiming to better understand the subjective reality of adolescents living with T1D and facilitate a more intricate understanding of their subjective perceptions surrounding 24-h MB that a positivist approach may not capture. To facilitate the practical implications of the research, pragmatism concepts were also considered for study three. The combination of interpretivism and pragmatism allowed for a better understanding of experiences through the lens of adolescents living with T1D and facilitate the potential incorporation of a 24-h MB approach into T1D management.

6. Qualitative research methods

The most common forms of qualitative research methods are semi-structured interviews, focus groups, document study and observation. These methods can be chosen based on the underlying substantive theory used by the researcher (Busetto, Wick, & Gumbinger, 2020). Due to study three being underpinned by an interpretivist theoretical perspective, semi-structured interviews were selected as the research method for study three.

Interviews are perhaps the most traditional method linked to qualitative research. They provide an opportunity for an in-depth exploration of how interviewees experience and perceive phenomenon of interest (Côté & Turgeon, 2005). Interviews are most appropriate when research is aiming to understand the subjective experiences of participants as opposed to generating generalisable findings.

Prior to any interview being conducted, the correct ethical measures must be applied and consent obtained. Additionally, careful logistical and conceptual planning should take place prior to interviews that consider the core research question (Brinkmann & Kvale, 2015). Logistical considerations include familiarisation with data recording apparatus; confirmation of a time and date suitable for participants and selection of a venue that limits distractions and facilitates discussion (Illing, 2013). Conceptual considerations include whether interviews will be semi-structured, structured or unstructured and ensuring the questions included in the interview guides are developed accordingly. For semi-structured interviews, the interview guide includes only a few predetermined questions with flexibility to delve into other topics arising from the conversation, while a structured interview utilises predetermined questions that are asked to all interviewees in a similar manor with minimal deviation from the script. Finally, unstructured interviews are characterised by an absence of interview guides, allowing for conversation to flow more freely (Ruslin, Mashuri, Rasak, Alhabsyi, & Syam, 2022). It is crucial interview guides are developed in advance and tested in a 'mock interview' at least once prior to the interview to bypass any potential logistical issues, hone interview skills (e.g., active listening) and ensure the questions are clear with appropriate use of language (i.e., avoid use of excessive jargon) (Jacobsen, 1993). Throughout the interviews some questions asked in the interview guide might be misunderstood or irrelevant to the overarching research question. Therefore, adjustment of the interview guide is permitted and will ultimately aid in the quality and richness of the data produced.

Building rapport with participants is crucial to ensure they trust interviewers enough to disclose highly personal information about their own experiences on a given phenomenon. It is advised that this rapport is built well in advance of the interview itself. This might be done by having an initial conversation about the research itself or drafting a short summary of the research so participants are better prepared for the discussion (DiCicco-Bloom & Crabtree, 2006).

The interviews conducted for study three were semi-structured and conducted via Zoom. Semi-structured interviews allowed for discussion to be guided, which is important for this age group while also providing flexibility to explore participant responses through probing for deeper insights. The interview discussion was centred around adolescents' experience with their diabetes management which can be a sensitive topic. Conducting the interview via Zoom allowed discussions to take place within their home environment and was thought to increase comfort and lead to richer and more honest discussions. Additionally, hosting interviews online allowed for a greater reach of participants across the UK and reduced logistical barriers present (e.g., travel, compensation etc). However, it is important to acknowledge that virtual interviews may limit the observation of non-verbal ques and contextual factors, which can constrain depth of interpretation and may also represent challenges in rapport building and data richness compared to in-person approaches (Oliffe et al., 2021).

6.1 Interview guide development

Prior to semi-structured interviews, it is recommended interview guides are developed containing nonjudgmental questions that are detailed enough to provide direction in conversation yet open enough to allow unanticipated discussion to emerge (Charmaz, 2014). This is a crucial part of the qualitative data collection process and requires careful thought and planning surrounding what questions are being asked, why they are asked and importantly, *how* they are being asked. Additionally, interview guides are particularly useful for novice researchers to ensure the interview and participants are focused on the research question and to facilitate the momentum of interviews, which is especially important for groups that are less open to sharing (Corbin & Strauss, 2014; Rubin & Rubin, 2011).

Interview guides are typically broken into specific sections containing orientating questions, main questions, follow up questions and probs. Initially, it is recommended the interviewer orientates the participants to the session by introducing themselves and the topic(s) that will be covered. Additionally, interviewers should aim to create a relaxed environment where participants can talk freely by displaying interest in everything and anything that is communicated. Additionally, participants should be assured that no information will be shared beyond the interview. In doing this it creates a relaxed environment where participants can talk more freely which will ultimately increase the likelihood of richer more authentic qualitative data (Bertaux, 1981; Brinkmann & Kvale, 2015). To ensure participants are comfortable with speaking during the session it is recommended opening questions or ice breakers are asked to illicit conversation and build rapport before the main bulk of discussion (Mepieza, 2024).

Main questions in the interview guides aim to address the research question most directly and are often informed through a review of the literature to ensure most relevant concepts are explored. A technique used when developing the main questions within an interview guide is to break the research topic into specific areas and develop a question to address each area (Rubin & Rubin, 2011). It is recommended to incorporate follow up questions to ask after the main question. These are used to facilitate a deeper understanding of the phenomenon of interest by delving deeper into the differing dimensions of the initial response. Additionally, follow up questions can also be used to seek clarification from participants if a response is ambiguous. Probing can also be detailed within the interview guide and can be verbal (e.g., “uh-huh,” “yes,” “okay,” “go on,” “Can you give me an example,”) or non-verbal (e.g., gestures, facial expressions, nods, body posture, and silence). Finally, closing questions (e.g., Is there anything else you would like to add to the discussion today?”) might be included at the end of interview guides to ensure everything has been discussed and gives the participant the opportunity to raise any issues, concerns or questions (Roberts, Yi-Frazier, Carlin, & Taplin, 2020).

For study three a semi-structured interview guide was developed containing a welcome and topic overview (i.e., interviewer introductions), ground rules discussion (i.e., setting the tone, confirmation of privacy, informal conversation with no right or wrong answers), opening question (i.e., ice breaker question), main questions with follow up questions), closing questions and thank you (i.e., participant further questions or concerns, thank you for time, summarise next steps). The semi-structured interview guide can be found in **Appendix R**.

7. Transcription

Transcription involves transformation of spoken word or recorded audio into written form (Duranti, 2006). There are two types of transcription that exist on a spectrum, which are intelligent verbatim (naturalised transcription) and full verbatim (denaturalised transcription) (Bucholtz, 2000). Full verbatim transcription is where everything is included for example, utterances, repetitions, mistakes and incorrect grammar. Additionally, all nonverbal cues (e.g., tone, laughter, punctuation) and contextual information (interruptions, cross talk and inaudible moments) are included. Utilising or omitting any verbal cues, nonverbal cues and contextual information can alter the meaning or intention of what an individual says substantially. Therefore, including everything offers a highly authentic account of the conversation and how it was presented in its original spoken form (Lapadat, 2000). However, choosing to utilise full verbatim transcription for certain groups where high repetition, incoherence and limited articulation is prevalent may result in unethical stigmitisation of that group (Kvale, 1996). Intelligent verbatim involves removing certain utterances, repetitive language, grammar and slang which can ensure stigmatisation of groups is avoided however, with intelligent verbatim transcribers essentially decide what they deem as important to include and remove resulting in the increased likelihood of the transcribers prior knowledge, assumptions and biases influencing the true meaning of what was originally expressed (Jaffe, 2007).

When transcribing, it is crucial to consider the transcriber's expertise. Ideally, transcribers should have subject-specific knowledge, language proficiency, and familiarity with the population studied. To minimize misalignment, it is recommended that the same person who develops the research questions and data collection methods handles transcription. Additionally, having researchers conduct both interviews and transcription ensures accuracy, as they can incorporate contextual insights from the interviews (McMullin, 2023).

Transcription for this study was completed by the primary researcher. Therefore, they had specialist knowledge of the subject matter, had developed the interview guide and conducted the interview so had all the relevant contextual information that might influence the conversation meaning. Transcription predominantly utilised intelligent verbatim (naturalised transcription) due to the amount of utterances, repetitions, grammar issues and slang occurring within the adolescents interviews. Additionally, it was deemed utilisation of full verbatim for adolescents might create an unethical stigmatisation of that group. Transcription was completed without the use of software or AI so that the researcher could familirise themselves with the data prior to developing themes and any contextual information (e.g., interruptions, crosstalk and inaudible segments) could be included to truly capture the original meaning and nature of conversation.

8. Analytical Approach

Consistent with study threes interpretivist theoretical and pragmatic perspectives, thematic analysis was utilised to explore adolescents subjective experiences of living with T1Ds. Thematic analysis is used to organise and define qualitative data by recognising, analysing and composing themes (Braun & Clarke, 2006). These themes can be identified either inductively (bottom up) or deductively (top down). Inductive thematic analysis is data driven, where theme development is not influenced by pre-existing theories. Instead, they are created from the ground up and is often compared to grounded theory. It is useful to utilise an inductive approach when little is known about the topic however, it is realistically difficult to conduct as researchers approach their work with certain theoretical and epistemological assumptions that are hard to completely abandon (Patton, 1990).

Alternatively, deductive thematic analysis is analyst-driven, where themes are developed based on theoretical assumptions and/or research interest in the area. Deductive approaches provide a more detailed analysis on specific aspects of the data making findings interpretable in a specific context and ensure a focused and systematic approach. However, this approach may lack a rich description of the data overall and risks overlooking unexpected insights through pushing data to answer pre-determined questions. Deciding on whether to adopt an inductive or deductive approach to thematic analysis depends on if the researcher is coding for a specific question (aligned to theory) or if the researcher wants the research question to evolve through the coding process.

Braun and Clarke (2006) described thematic analysis as an iterative process that moves recursively between six key phases including: 1) familiarising yourself with the data; 2) generating initial codes; 3) searching for themes; 4) reviewing themes; 5) defining and naming themes and 6) producing the report. Initially, it is crucial researchers familirise themselves with the data.

Researchers who conducted data collection methods and performed transcription themselves (i.e., conducted interviews) will immediately have prior knowledge on the data and preformed ideas of potential themes (Riessman, 1993). Further familiarisation might involve repeated 'active' reading where the research is actively analysing text for an initial list of ideas about the content of the data and what is interesting about them.

The second phase involves generating the initial codes, which are sub-units of the main units of analysis (themes) and can be done through note writing, highlighting sections of text or using post it notes for segments of data. When coding it is important to code for as many potential patterns as possible, ensure information relevant to the codes context is not omitted and that codes can be included in many different themes and can also be uncoded.

The third phase involves sorting codes or combinations of codes into overarching themes and sub themes. At this stage one might also have codes that do not align to any overarching theme and one might want to create a miscelleneous theme. At this stage it is helpful to utilise visuals to facilitate understanding of codes/themes and the relationships between them (e.g., tables, mind-maps, thematic maps).

Phase four involves reviewing the set of potential themes identified in phase three and has two distinct levels. Level one involves reviewing the coded data and requires researcher to read all collated extracts for each theme and determine if they correctly align to that theme. If they do not, then the researcher would adjust the codes or theme (i.e., create a new theme, reword existing theme, discards extracts or home them in another code). Once this is completed, the second level of this phase can be completed. Level two involves reviewing the entire data set to determine if themes make sense in the context of the data set and to ensure no data has been missed at earlier dating coding stages.

Phase five involves defining and naming the themes for analysis. A crucial part of this phase is to ensure researchers do not paraphrase the extracts within the theme and really aim to understand and communicate their core meaning and why it is interesting in relation to the research. At the end of this phase, it is crucial the researcher knows exactly what each of these themes are and can be summarised in only a few sentences. The final stage involves writing up the report and can be done when all the themes and sub themes have been determined. The results should provide evidence of the themes through careful selection of relevant quotations (e.g., vivid, diverse and illustrative to specific theme).

Thematic analysis can be conducted on several different software packages designed to streamline, enhance and improve research rigor (e.g., NVivo, ATLAS.ti, MAXQDA) (Hart & Achterman, 2023). NVivo is perhaps the most popular software due to its functionalities in data management, coding, analysis, visualisations, queries and reporting making it an extremely popular tool for qualitative researchers (Dhakal, 2022).

Thematic analysis for study three was predominantly completed by the primary researcher (M.P.) who generated the research questions, conducted interviews and transcribed the data. However, three additional researchers had input in the continuous revision of codes and themes (A.K., X.J., & M.C.). Codes and themes were developed using both an inductive and deductive approach. The research aimed to create codes from the ground up without too much influence from theoretical frameworks so that findings were authentic to the participant. However, the lead researcher had their own theoretical and epistemological assumptions on the topic area which may have influenced development of codes. The software NVivo was utilised for all six stages of thematic analysis and provided functionalities that streamlined work for all four researchers.

9. Positionality and role of the researcher

For researchers conducting qualitative research, it is crucial for them to be aware of their own and others positionality. Positionality describes a person's overall view of the world and how they might conduct research (Rowe, 2014). This view is informed largely by that person's own assumptions about reality (i.e., ontology), their assumptions about the creation of knowledge (i.e., epistemology) and their own assumptions surrounding human nature and agency (i.e., how we interact and relate to our own environment) (Holmes, 2020). Aspects of positionality can be described as fixed or fluid. For example, ethnicity and gender would be regarded as fixed while political views and personal history regarded as fluid (Chiseri-Strater, 1996). Fixed aspects of positionality might shape a person's opinions or viewpoints however, they do not guarantee them, and assumptions should therefore not be made. Importantly, a person’s positionality is in constant flux as their values and perceptions change over time dependent on their experiences and exposure to certain situations (Rowe, 2014). An important consideration of positionality is the insider-outsider debate and describes an insider as members of the group under investigation and outsiders as non-members (Merton, 1972). A researcher with an insider positionality may have a profile that aligns with the participants such as gender, race, sexuality and gives them prior knowledge of a group. Alternatively, a researcher with an outsider positionality may not have a profile that aligns with the group under examination and limited knowledge of that group (Mercer, 2007). There are several advantages and disadvantages of insider-outsider positionality. Generally, the advantages of a researcher with insider positionality are: 1) easier access to participants as they are viewed as being part of the community/culture; 2) prior knowledge of the group will improve the development of meaningful questions; 3) improved trust/rapport resulting in richer and data with improved validity; 4) increased likelihood of a truthful and more accurate interpretation of results; 5) disorientation surrounding the culture being investigated is removed or reduced and 6) language (verbal and non-verbal) is better understood. The disadvantages of insider positionality include: 1) research unrecognised biases towards group; 2) familiarity with the culture resulting in the resistance to ask difficult or challenging questions; 3) researcher is deemed an expert of the group already so participants may not feel the need to disclose certain information; 4) an inability to provide external perspectives; 5) questions that seem mundane will not be asked even though they could result in important information/discussion, and 6) participants may be more resistant to disclosing any sensitive information to someone they may see in their community/group again (Holmes, 2020).

Finally, it is important for the interviewer to understand their role as a researcher. Researchers should consider themselves as co-creators of the data, where their knowledge and expertise can facilitate discussion. Researchers are essentially the tool used to gather information and are therefore required to be reflexive, conscious, and aware about how their role might impact the findings (Lingard & Kennedy, 2010). For example, interviewers can add bias to the discussion or be unaware of the cultural and power dimensions of the interview situation (Nimmon & Stenfors-Hayes, 2016).

10. Reflexivity

A researchers positionality can influence each stage of the research process and it is therefore important for researchers to engage in reflexivity to continuously assess their positionality and reduce the likelihood of their research being influenced (Foote & Gau Bartell, 2011). Reflexivity involves researchers constantly assessing, recognising and disclosing themselves within their research in a bid to better understand their role and influence on the research (Cowan, 2011). This means researchers must be sensitive and hyper aware of their own fixed and fluid aspects of their own positionality and consider these in light of the research processes/interpretations and how they might affect them (Bourke, 2014; Bryman, 2016). However, even with extensive reflexivity researchers will still have a level of bias and subjectivity towards their research because experiences and language interpretations are inherently subjective (Von Glasersfeld, 1998). Additionally, Holmes (2019) posited that individuals have aspects of themselves they are unaware of and when reflecting, they may be resistant to excepting aspects of themselves. Therefore, how can someone be truly reflexive towards their research if their own subjectivity and lack of self-transparency are present. Essentially, the ability for researchers to escape the social world they inhabit in order to study it is near impossible (Hammersley & Atkinson, 2019; Malterud, 2001). However, clear documentation of a researchers positionality is still valuable as it provides the reader with an additional layer of context that might have shaped the research process and interpretation of findings (Sikes, 2004).

Savin-Baden and Major (2023) discuss three ways in which researchers can establish their positionality. They suggest researchers 1) describe the research through their eyes (i.e., personal, theoretical and philosophical beliefs and how these influence research process); 2) disclose the potential influences on the research (i.e., age, gender, social class, religion, education, career); 3) disclose their pre-determined position in relation to the participants in the research (i.e., insider or outsider); 4) describe the research context and how this might have shaped the research processes (i.e., that the research will be influenced by the researcher) (Savin-Baden & Major, 2023).

10.1 Positionality statement

As a researcher investigating the 24-h MBs of adolescents with T1Ds, I recognise the influence of my background, experiences, and values on the research process. I am a white woman from an upper/working-class background. Growing up as the youngest in a large family, I was shaped by my experiences of caregiving for my older sister and by the privilege I experienced during my upbringing. These experiences have contributed to my understanding of inclusivity and the challenges faced by marginalised groups.

Movement behaviours have always been central to my life, both personally and professionally. As a competitive athlete, I deeply value the role of healthy movement behaviours in promoting physical, mental, and social health. My academic background includes a BSc in Sport and Physical Activity from the University of Strathclyde, an MSc in Exercise as Medicine from Loughborough University, and my current PhD research at Strathclyde, reflects this commitment to understanding and improving movement behaviours for health.

While I had no direct connection to T1D when I began my PhD, this changed in 2020 when a close family member was diagnosed with the condition. This personal connection has given me greater empathy for the lived experiences of those managing T1D. However, I am conscious that I do not share an insider perspective, as I do not have the condition myself. To address this, I openly discussed my family connection during interviews to build rapport and acknowledge my position as a partial outsider.

I am aware of the power dynamics present in my research. As an adult and a PhD researcher, I recognise that my age, academic status, and lack of direct lived experience with T1D may have influenced participants' perceptions of me. These dynamics may have created barriers to open communication or contributed to a sense of formality during our interactions. To mitigate these effects, I aimed to create a comfortable and non-judgmental environment, emphasising my role as a learner rather than an authority figure.

Throughout the research process, I have been committed to reflexivity. One challenge I encountered was a moral barrier during participant recruitment, particularly when engaging with online T1D communities. While these groups offered valuable opportunities to connect with potential participants, I felt like an imposter in spaces where individuals shared deeply personal struggles and sought support for their condition. Posting about my research in these contexts often felt intrusive, as it did not address the immediate challenges faced by this community. This experience highlighted the ethical complexities of recruitment and underscored the importance of approaching these communities with sensitivity and respect.

My positionality as a researcher is shaped by my professional expertise in movement behaviours and health, my personal experiences with caregiving and privilege, and my evolving understanding of the T1D community. By remaining reflexive and acknowledging the power dynamics and moral challenges inherent in the research process, I strived to conduct this study with integrity, empathy, and a commitment to amplifying the voices of adolescents with T1D.

11. Overview of rationales for study three

Based on the review of literature, data collection and analytical decisions were selected to ensure the experiences of adolescents living with T1Ds perspectives and experiences of 24-h MBs is captured accurately. **Table 5.2** summarises these considerations alongside the rationale for each choice.

Table 5.2: Summary of qualitative decisions and rationales for study three.

Qualitative Considerations	Decision	Rationale
Research paradigm	Interpretivist and pragmatist.	Understand subjective reality and consider practical implications.
Qualitative data collection method	Online semi-structured interviews.	Structured conversaton suitable to population; home environment to facilitate discussion; online provided greater reach of participants.
Transcription	Utilised intelligent verbatim, no transcription software used.	Limits utterances and avoids unethical stigmitisation; ensures familiarity of the data.
Analytical approach	Thematic analysis used inductively and deductively using NVivo software.	Aligns to interpretivism and pragmatism concepts.
Positionality, role of the researcher & reflexivity	Positionality statement developed.	Increased awareness of positionality

12. Study three: If You Haven’t Slept a Lot (…) You Don’t Want to Go Out for a Run, You Don’t Want to Ride a Bike, You Just Kind of Sit and You Just (…) Do Nothing”—Perceptions of 24-Hour Movement Behaviours Among Adolescents Living with Type 1 Diabetes

International Journal of
Environmental Research and Public Health

MDPI

Article

"If You Haven't Slept a Lot (...) You Don't Want to Go Out for a Run, You Don't Want to Ride a Bike, You Just Kind of Sit and You Just (...) Do Nothing"—Perceptions of 24-Hour Movement Behaviours Among Adolescents Living with Type 1 Diabetes

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Abstract

The importance of physical activity, sedentary behaviour, and sleep behaviour in adolescents with type 1 diabetes (T1D) has been explored in isolation. However, adolescents experience health benefits when these behaviours are balanced appropriately throughout the day, and are considered to be interconnected rather than isolated. The aim of this study was to investigate the perspectives of adolescents living with T1D towards these behaviours collectively. The participants were 15 adolescents (aged 11–18 years) with T1D, recruited using online methods and word of mouth. Online semi-structured interviews were transcribed using intelligent verbatim and analysed using thematic analysis. We identified the following four central themes and five subthemes: (1) sleep and physical activity are understood and valued above sedentary behaviour; (2) recognition of movement behaviours' interconnection; (3) movement behaviours' interaction with health outcomes (mood, glycaemic control, and glycaemic control as a barrier to movement behaviours); and (4) movement behaviours within the environmental context of the adolescent (school and caregivers). Adolescents with T1D are aware of the interconnectedness of each movement behaviour and the positive influence a balanced approach can have on mood and T1D management. The findings provide important information for future holistic interventions promoting healthy behaviours that target the adolescent, their school environment, and their caregivers.

Keywords: adolescent; sleep; physical activity; sedentary behaviour; type 1 diabetes; qualitative; 24-hour movement behaviours

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Academic Editors: Yi-Sub Kwak and Paul B. Tchounwou

Received: 16 May 2025
Revised: 17 July 2025
Accepted: 2 August 2025
Published: 19 August 2025

Citation: Patience, M.; Kirk, A.; Janssen, X.; Sanders, J.; Crawford, M. "If You Haven't Slept a Lot (...) You Don't Want to Go Out for a Run, You Don't Want to Ride a Bike, You Just Kind of Sit and You Just (...) Do Nothing"—Perceptions of 24-Hour Movement Behaviours Among Adolescents Living with Type 1 Diabetes. *Int. J. Environ. Res. Public Health* **2025**, *22*, 1295. https://doi.org/10.3390/ijerph22081295

1. Introduction

Type 1 diabetes (T1D) necessitates 24-hour management, involving careful and constant monitoring of blood glucose levels, insulin administration, and lifestyle adjustments [1]. This attention and adaptation creates unique challenges, particularly for adolescents, who form a significant demographic of those living with type 1 diabetes and already navigate a myriad of changes associated with adolescence (e.g., increased autonomy, expanded social interactions, and physiological transformations) [2,3]. Every aspect of their daily routine holds implications for glucose control and management decisions, including the triad of movement behaviours performed during a 24 hour day, namely, physical activity (PA), sedentary behaviour (SB), and sleep.

Research has consistently demonstrated the positive effects of increased physical activity and reduced sedentary behaviour on glucose control and psychosocial outcomes within the type 1 diabetes adolescent population, and they are recognised as a cornerstone of type 1 diabetes management. Guidelines recommend at least 60 min of moderate–vigorous intensity PA (MVPA) per day and to limit sedentary behaviour [4–6]. Although there are no sleep guidelines specific to this population, suboptimal sleep duration and poor sleep quality in this population have been recorded. A bi-directional relationship between sleep and glycaemic control has been evidenced by sleep disturbances related to glucose variability, diabetes distress, and the completion of important type 1 diabetes self-management activities in adolescence [7–9]. However, no research has investigated how combinations of all three behaviours interact and impact on important type 1 diabetes outcomes [10].

The 24-hour movement behaviour (24-h MB) approach argues for the combined examination of all movement behaviours [11]. Physical activity, sedentary behaviour, and sleep should be treated as part of a continuum from no movement [12] to high movement (vigorous physical activity). These behaviours are considered to be relative or time-dependent, meaning a change in one behaviour can impact another. Importantly, the way these movement behaviours are combined throughout the day has significant implications for the physical and mental health of adolescents [13,14]. This evidence has resulted in the development of 24-h MB adolescent guidelines and the incorporation of key 24-h MB principles in global movement behaviour guidelines, highlighting the detrimental effect of sedentary behaviour on sleep duration, the positive influence of physical activity on sleep, and the importance of replacing sedentary behaviour with physical activity [15,16].

The current qualitative research on adolescents with type 1 diabetes has investigated perceptions of sleep, sedentary behaviour, and physical activity individually; however, no study, to our knowledge, has investigated how adolescents with type 1 diabetes collectively understand these behaviours [9,17–19]. Given the increased attention towards a 24-h MB approach, the evidence indicating the influence of each behaviour on important type 1 diabetes outcomes, and the 24-hour management required for type 1 diabetes, a holistic—rather than isolated—approach towards movement behaviours should now be considered. A crucial step towards this is to initially investigate the current understanding of adolescents living with type 1 diabetes towards the interconnected nature of these behaviours and how they might impact health. This provides a starting point in the development of effective interventions aimed at supporting type 1 diabetes management in this population.

2. Materials and Methods

2.1. Study Design

This qualitative study was part of a larger piece of research exploring 24-h MBs in adolescents living with type 1 diabetes with both quantitative (questionnaire and wrist-worn accelerometer) and qualitative elements. Semi-structured interviews were conducted after the individual completed the quantitative part of the research project. The qualitative approach was informed by concepts of interpretivism, aiming to understand the experiences and perceptions of movement behaviours of adolescents with type 1 diabetes [20]. Additionally, pragmatism concepts were considered for this study to facilitate the practical implications of the research [21]. The University of Strathclyde Research Ethics Committee reviewed and approved this research (UEC22/04) on 27 April 2022.

2.2. Participants

Participants were eligible for this qualitative study if they were aged 11–18 years, were diagnosed with type 1 diabetes, currently lived in the UK, spoke English, had no mobility-related issues or required walking aids, and had not been diagnosed with a sleep disorder (self-reported). These exclusion criteria were applied to reduce potential confounding factors that could independently affect movement behaviours. Recruitment materials included infographics and a video of the lead researcher describing the research, aiming to engage the target group more successfully [22].

Participants were recruited using online methods (e.g., social media) and word of mouth. Diabetes charities and type 1 diabetes influencers were involved in the dissemination of recruitment materials throughout a six-month period between March 2023 and August 2023. Recruited participants completed a prior study involving accelerometer-based measurement of their movement behaviours. Although behavioural diversity was not used as a recruitment criterion, the sample reflected a range of movement profiles, including differences in physical activity, sedentary behaviour, and sleep duration, as observed in the accelerometer data. Not all participants provided valid movement behaviour data due to insufficient wear time. However, all who were enrolled completed the qualitative interview, and no participants were lost to follow-up.

Interested individuals were then directed to an initial questionnaire to assess eligibility and the appropriate consent pathway. Participants provided consent to conduct the study and publish the study. For adolescents aged 11–15 years (younger adolescents), written consent was obtained and a verbal consent meeting was conducted with the adolescent and their caregiver to gain verbal consent/assent. For adolescents aged 16–18 years (older adolescents), written consent was obtained.

2.3. Data Collection

Upon enrolment into the study, participants completed a questionnaire that assessed demographic information and diabetes-specific information (e.g., insulin delivery and blood glucose measurement methods, diabetes duration, and mean haemoglobin A_{1c} (HbA_{1c})). Health-related quality of life was measured using the validated Paediatric Quality of Life (PedsQL) 3.2 Diabetes Module for adolescents with type 1 diabetes (use of this questionnaire was approved by the author in December 2021) [23]. After returning an ActiGraph GT3X-BT accelerometer (please see Supplement S1 for accelerometer data processing methods), an interview was scheduled for those who agreed to take part in this qualitative part of the study.

Semi-structured interviews were arranged at a suitable time for participants and were conducted online via Zoom, allowing for audio and video recording [24]. All participants completed the interviews within their home environment and without a caregiver present to ensure the conversation was not influenced and communicated perceptions were original. Interviews were conducted by the lead researcher, a 28-year-old female currently completing her PhD, who had trained in video conferencing platform interview techniques and specialised in qualitative methods during their Master's degree (M.P.; MSc). Rapport had previously been established between the interviewer and adolescent during the accelerometer data collection phase. Rapport is theorised to enhance trust and confidence, resulting in improved discussion [21]. The interview utilised an informal conversational style and was guided by an interview schedule to ensure consistency of discussion across all interviews, and was piloted prior to data collection to increase reliability (Supplement S2).

The interview began with the interviewer introducing themselves and their background and detailed the purpose of the conversation, which was to discuss physical activity, sedentary behaviour, and sleep, and that these were all the activities the individual might take part in during a 24 hour day. Adolescents were informed there were no right or wrong answers and to let the researcher know if they would like to stop or had any issues throughout the discussion. Adolescents were asked an 'ice breaker' question prior to the main discussion to allow the adolescent to relax and become comfortable with the discussion [25].

Interview questions were open-ended and prompts were utilised throughout to obtain greater detail and depth of discussion [26]. Data saturation (i.e., additional data no longer yielded new insights, themes, or information) was obtained at 15 participants, and recruitment stopped [27]. Data saturation was confirmed when no new themes emerged in the final two interviews and was verified through weekly debriefs with the research team, where the interview content and coding progress were collaboratively discussed. This is consistent with current research, suggesting that saturation is typically achieved within 9–17 interviews in studies with homogenous populations and focused research aims [28].

2.4. Data Analysis

The recordings of the interviews were transcribed using intelligent verbatim due to the volume of utterances and repetitions present within this age group [29]. Additionally, this ensured that no unethical stigmatisation of this group was conveyed [30]. Transcription was completed by the researcher who conducted the interview to ensure familiarity of the data. Throughout the transcription process, potential themes and reoccurring concepts were noted. Participant names were removed from the transcripts and replaced with their participant ID to ensure anonymity. Transcribed interviews were transferred to NVivo version 20.7.1 (Qualitative Solutions and Research International) to facilitate the organisation of codes, themes, subthemes, and relevant quotations.

There were four researchers involved in the coding of data. Interview data was primarily analysed by the lead researcher (M.P.), with continuous revision and input (A.K., X.J., and M.C.) using thematic analysis [31]. Thematic analysis is an iterative process moving between six phases to identify and analyse patterns within data. The six phases involve (1) familiarisation of the data (transcribing, reading, and annotating interview transcripts); (2) generating initial codes (listing initial interesting ideas and organising these into meaningful groups); (3) searching for themes (sorting codes into subthemes); (4) reviewing themes (refining themes, ensuring codes within themes are cohesive, and ensuring distinctions between themes); (5) defining and naming themes; and (6) producing the report (themes written and demonstrated through quotations). The defining of codes was mainly inductive; however, the lead researcher had a theoretical understanding of potential topics that may have arisen in the data, so the definition of codes could also be deductive.

2.5. Researcher Reflexivity

The lead researcher acknowledged and addressed their own biases, preconceptions, and personal experiences that could impact data collection and interpretation through reflexivity prior to the interviews (e.g., reflection on own biases, beliefs, and values), post interview (e.g., interview and participant impressions), and during the analysis of data (e.g., rationale for themes/codes and initial impressions of data) [31,32].

For example, the researcher acknowledged a belief in the value of movement behaviours for health as well as the potential power dynamic between the researcher and participant, and understood that they had no lived experience of movement behaviours in the context of type 1 diabetes that may have influenced the question-phrasing or the emphasis placed on certain topics. To mitigate this, a semi-structured interview guide was used. Additionally, a brief statement was developed to remind the researchers of their position throughout the research stages ("I value movement behaviours and recognise my position as an adult researcher without lived experience of type 1 diabetes. I hold awareness of my power and perspective and will listen without assumption").

3. Results

3.1. Participant Demographics

In total, 15 adolescents (6 male; 9 female) participated, averaging 14.6 ± 2.0 years in age (8 younger adolescents; 7 older adolescents), with the majority identifying as white British (n = 14). Participants had a diabetes duration of 3.7 ± 3.1 years; an HbA_{1c} of 57 mmol/mol (7.4 ± 1.0%), which is within the recommended target values for HbA_{1c} in this age group; and a mean PedsQL 3.2 total score of 62.7 ± 14.3, indicating good quality of life. The sample predominantly used continuous glucose monitors (CGMs) (80%) and insulin pumps (67%) and, according to the accelerometer data collected, were sleeping 8.1 ± 0.7 h·per day, performing 28.1 ± 24 min·per day of MVPA, and had 9.8 ± 1.7 h·per day of sedentary time (Table 1).

Table 1. Participant characteristics for the full sample. Frequency data is given as number (%); descriptive data is given as mean ± standard deviation (M; SD).

Characteristic	Full Sample (n = 15)
Interview Length (Minutes)	23 ± 6.5
Age	
Younger Adolescent (11–15 Years)	8 (53.3)
Older Adolescent (16–18 Years)	7 (46.7)
Sex	
Female	9 (60)
Male	6 (40)
Ethnicity	
White	15 (100)
Insulin Delivery	
Pen	5 (33.3)
Pump	10 (66.7)
Blood Glucose Measurement Method	
CGM	12 (80)
Finger-Prick	3 (20)
Age (Years)	14.6 ± 2.0
Diabetes Duration (Years)	3.7 ± 3.1
HbA_{1c} (%)	7.4 ± 1.0
Paediatric Quality of Life Total Score	62.7 ± 14.3
Sleep (Hours·per Day) [a]	8.1 ± 0.7
SED (Hours·per Day) [a]	9.8 ± 1.7
MVPA (Min·per Day) [a]	28.1 ± 24

HbA_{1c}: haemoglobin A1c; CGM: continuous glucose monitor; SED: sedentary behaviour; MVPA: moderate-to-vigorous physical activity. [a] 24-hour movement behaviour data, using actigraphy available from 12 participants.

There were four major themes and five subthemes identified through the investigation into the perspectives and values towards movement behaviours, collectively, of adolescents with type 1 diabetes (Table 2). These are presented and supported with quotes from the adolescent. Figure 1 was created to conceptualise adolescents' perceptions of 24-h MBs within the context of type 1 diabetes.

Table 2. Codebook of themes.

Theme	Subtheme	Definition
Theme 1: Sleep and PA understood and valued above SB		Adolescent understands and values sleep and PA more than SB
Theme 2: Recognition of movement behaviours' interconnection		Adolescent perceptions on how sleep, PA, and SB might interact and impact one another
Theme 3: Movement behaviours interaction with health outcomes	Mood	Adolescent perceptions on how sleep, PA, and SB interact with their mood
	Glycaemic control	Adolescent mixed perceptions on how sleep, PA, and SB interact with their glycaemic control
	Glycaemic control as a barrier to movement behaviours	Adolescent perceptions of glycaemic control as a barrier to movement behaviours
Theme 4: Movement behaviours within the environmental context of the adolescent	School	Adolescent perceptions of school and how it affects their sleep, PA, and SB participation and understanding
	Caregivers	Adolescent perceptions of their caregivers' role in their sleep, PA, and SB

PA: physical activity; SB: sedentary behaviour.

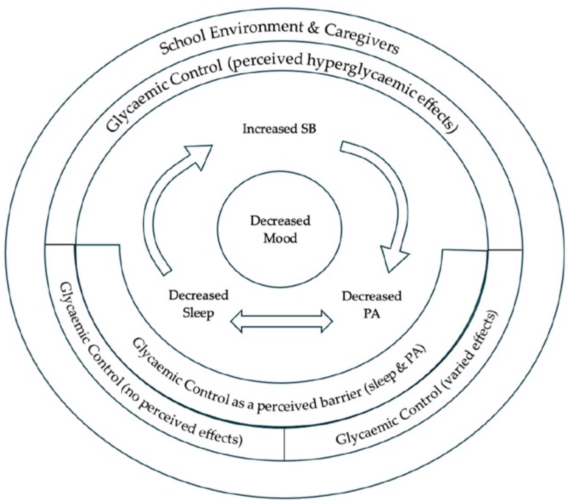

Figure 1. Conceptual representation of adolescents' perceptions of 24-hour movement behaviours within the context of type 1 diabetes. At the centre, adolescents understood a cycle between sleep, physical activity (PA), and sedentary behaviour (SB), where increased SB led to a decrease in PA and, ultimately, decreased sleep. Importantly, adolescents acknowledged that this cycle had negative effects on mood. Adolescents also understood a bi-directional relationship between PA and sleep (indicated by the double arrow). Adolescents frequently discussed glycaemic control as a barrier to sleep and PA. Conversely, adolescents perceived each behaviour to have differing effects on glycaemic control. Adolescents perceived SB to have hyperglycaemic effects, PA was perceived to have varied effects on glycaemic control, and sleep had no perceived effects on glycaemic control. School environment and caregivers were frequently discussed by adolescents as contextual forces shaping movement behaviours and subsequent outcomes.

3.2. Theme 1: Sleep and Physical Activity Understood and Valued Above Sedentary Behaviour

When asked about all three movement behaviours, it was clear that sleep and physical activity were considered in adolescent lives, whereas sedentary behaviour was not consciously considered. One adolescent discussed sleep and physical activity and how these behaviours integrated into their life but needed reminding of sedentary behaviour. Even when adolescents were prompted, they struggled to discuss sedentary behaviour, with one adolescent explaining that they did not consider it within their day. Adolescents were aware of sleep and physical activity guidelines but had less awareness of sedentary behaviour guidelines. The prioritisation of sleep and physical activity was further highlighted through adolescents discussing how they tracked the two behaviours using their own wearable devices but omitted discussion of sedentary behaviour tracking. One adolescent expressed surprise that sedentary behaviour was tracked by their own wearable device, which was only realised during the interview.

> *"Physical activity, well it depends how old you are, but I think it's an hour a day or something like that on average and then seven to eight hours of sleep, honestly, I have no idea about sitting."* (P12, female, and 16 years of age).

> *"The only thing I really track is how many steps I've done and how much sleep I get."* (P6, male, and 14 years of age).

> *"I think I can get a bit obsessive with things that show you so exactly like an Apple Watch does. I noticed that I was doing that—oh it had stand hours on it! Sorry I just realised that for the sitting thing."* (P3, female, and 18 years of age).

3.3. Theme 2: Recognition of Movement Behaviours' Interconnection

Throughout the discussion, adolescents exhibited an underlying awareness of the relative or time-dependent principles underpinning a 24-h MB approach. They expressed understanding that a change in one behaviour can have a significant impact on another. Adolescents understood the interconnectedness of all three movement behaviours and discussed a "cycle" between sleep, physical activity, and sedentary behaviour. They believed that their participation in sedentary behaviour was at the expense of their physical activity, ultimately resulting in adolescents experiencing poorer sleep. Adolescents also described how poor sleep resulted in physical activity being replaced with increased time spent sedentary. Adolescents understood how participation in one behaviour might affect another, highlighting the understanding of a bi-directional relationship between physical activity and sleep. Additionally, adolescents described how mood mediated the influence of good sleep on physical activity as well as the interaction between sedentary behaviour and physical activity. However, adolescents also perceived sedentary behaviour as relaxing and as a behaviour that would replenish them after physical activity participation.

> *"I am literally sitting at my desk all day working and I don't have time to do any kind of exercise. Then also that affects my sleep as well because I might be mentally tired, but I am not like physically tired because I have not done any physical activity which makes it a bit more difficult to get to sleep."* (P1, female, and 16 years of age).

> *"If you haven't slept a lot then the next day you don't want to be going out for loads of walks, you don't want to go out for a run, you don't want to ride a bike you just kind of sit and you just kind of do nothing."* (P11, female, and 17 years of age).

> *"If you have a more restful sleep and like a good sleep you will be more energetic so you will have more energy to do exercise."* (P10, male, and 16 years of age).

> *"If I do a physical activity then I would sit down after just because I'm tired."* (P6, male, and 14 years of age).

3.4. Theme 3: Movement Behaviours' Interaction with Health Outcomes

3.4.1. Mood

Adolescents discussed how they perceived movement behaviours to interact with their mood. They spoke about poorer sleep and higher sedentary behaviour producing negative moods while higher levels of physical activity produced positive moods. When adolescents discussed all three behaviours together, they discussed the combination of poor sleep, higher sedentary behaviour, and lower physical activity being detrimental to mood.

> *"I think if I'm sat down for long periods of time or even if it were short periods of time broken up for just a long day it just makes you feel a bit... you know. Yeah, and then, that can kind of effect your mood."* (P12, female, and 16 years of age).

> *"You can't just say 'I'm going to sit down and do nothing' you say, 'I am going to go do exercise because it's good for me', it's good for my physical and mental health."* (P14, male, and 13 years of age).

> *"If I have a day and I have been sitting around all day, I've not done any exercise and got no sleep I get really grumpy."* (P5, female, and 13 years of age).

3.4.2. Glycaemic Control

There were mixed perceptions from adolescents on how movement behaviours interacted with glycaemic control. Physical activities' interaction with glycaemic control was discussed in relation to different intensities of the behaviour. Adolescents recognised the short-term varying effects of different intensities of physical activity on glycaemic control. However, the effects of different physical activity intensities were confused at times. Adolescents discussed the hypoglycaemic effects of light physical activity but also highlighted light physical activity being used as a blood glucose management tool to bypass potential hyperglycaemic events. Adolescents highlighted that they were more likely to go hyperglycaemic if they had higher sedentary levels. Additionally, adolescents did not perceive better sleep to have direct effects on glycaemic control. Instead, adolescents mainly discussed sleep in relation to sleep interruptions due to glucose management requirements through the night.

> *"I've forgotten which way around it is but anaerobic and aerobic exercises. One will make your blood sugars go up and one of them will make you go down straight away."* (P14, male, and 13 years of age).

> *"If you're sitting, you might need to get up because if you've been sitting for too long your blood might go a little bit high."* (P4, male, and 14 years of age).

> *"I think the thing with sleep is it doesn't affect my blood sugars so the issue in sleep is if something happened that has made my blood sugar go low whilst I'm asleep."* (P1, female, and 16 years of age).

3.4.3. Glycaemic Control as a Barrier to Movement Behaviours

Glycaemic control was also discussed by adolescents as a barrier to movement behaviours, particularly sleep, where the discussion of sleep/night-time interruptions from diabetes technology (e.g., CGMs and pumps) was prevalent. Glycaemic control was a perceived barrier to physical activity, with many adolescents discussing the importance of ensuring that blood glucose was at an optimal level before physical activity could be performed.

> *"I am sleeping with an actual machine attached to me. It's more difficult, I think. I know I've had sleep issues since before I was diagnosed but notable ones since I was diagnosed."* (P3, female, and 18 years of age).

> *"When I was on my way home from school I was like 'oh it would be really nice to do a workout today' but I don't think I will be able to because I don't think I will be able to get my blood sugar to go up for long enough. That makes me feel annoyed because it's inconvenient. If that was someone without diabetes that wouldn't be a problem."* (P1, female, and 16 years of age).

3.5. Theme 4: Movement Behaviours Within the Environmental Context of the Adolescent

3.5.1. School

Throughout the discussions, adolescents highlighted how the school environment promoted physical activity, broke up sedentary behaviour, and facilitated better sleep. Although adolescents discussed how the school environment created opportunities to be active, often in relation to physical education, many discussed the barriers of performing physical activity within a school setting due to the resulting type 1 diabetes management requirements, which in turn created negative affective states such as anxiety and stress. Adolescents acknowledged school provided a structure that could break up long periods of sedentary behaviour and provide a good sleep routine. Another adolescent described how the school day provided a good structure to balance movement behaviours specifically for type 1 diabetes management. However, adolescents discussed how the school environment might promote an unhealthier balance of behaviours, such as schoolwork and exams promoting higher levels of sedentary behaviour and the challenges of early school start times, which were often intensified by the night-time awakenings caused by diabetes alarms.

> *"Physical activity, I probably should be doing more of it to be honest because I only really do it in school and maybe a bit at home."* (P15, female, and 12 years of age).

> *"I usually go to my bed at like half nine or ten now because I'm in a school routine but when I'm not it's kind of all over the place and my sleep pattern is just so all over the place. It kind of gets ruined and I feel icky."* (P9, female, and 16 years of age).

> *"So, at school I will find that it's kind of a decent environment because I will be sitting down for a couple of lessons for a few hours and then I go out with my friends for a walk which is a mile or so then come back. So, I find they balance each other fairly nicely."* (P11, female, and 17 years of age).

> *"I think just the social pressure of knowing that if my blood sugars were good and I went and did some form of physical activity, if I had a hypo in the middle of a gym hall that was embarrassing for me."* (P3, female, and 18 years of age).

> *"Sitting, I guess I do it a lot because I've got a lot of homework and then studying."* (P2, female, and 13 years of age).

> *"So, say I hadn't a decent nights sleep especially if my alarm had been going off or I didn't go to sleep till late and sometimes I have to wake up early for school. I will be tired and then I might be quite moody and then because I'm tired my levels might go high which then stresses me out because I will be at school, and I don't like injecting in public. So, then I might get more stressed, and it might make me quite anxious."* (P11, female, and 17 years of age).

3.5.2. Caregivers

When adolescents discussed their movement behaviour participation when they were younger, it was clear they believed that they had less autonomy in how they engaged in behaviours. Instead, adolescents highlighted the importance of their caregivers in engaging in these behaviours and recognised how they had more autonomy as they aged. Additionally, when adolescents were asked who they would ask for any information related to movement behaviours, they highlighted their caregivers. Finally, adolescents discussed how caregivers' own movement behaviours were impacted, particularly sleep, as they often woke to monitor their child's glucose levels throughout the night.

> *"When I was eleven, I would probably get more sleep because I would go to bed earlier, and my parents would expect me to go to bed earlier. But then as I get older, I go to sleep whenever I want, and you have potentially less sleep and also end up just getting less sleep to get up early to go to school and work."* (P1, female, 16 years of age).

> *"I'm a very deep sleeper so, if I've got a high I just sleep like this *imitates sleeping* and my dad just like comes in and says '[NAME]' and I'm like half-awake. So, he just types it into the pump anyway, so it is not an issue."* (P14, male, 13 years of age).

4. Discussion

This is the first study, to our knowledge, investigating the perceptions of adolescents living with type 1 diabetes towards all three movement behaviours together and how they might interact within a day. We highlighted four main themes of adolescents' perceptions towards these behaviours. Adolescents discussed the interconnected nature of all behaviours within a day, the importance of sleep and physical activity with a lower consideration of sedentary behaviour, the interaction that movement behaviours have with health outcomes, and movement behaviours' interaction with their environment.

Although previous research has consistently highlighted the benefits of reduced sedentary behaviour for adolescents with [5] and without type 1 diabetes, it appears that the importance of the behaviour has not been adequately conveyed to this population [33]. Within type 1 diabetes clinical care, sedentary behaviour accompanies physical activity and its importance is somewhat overshadowed. Current international physical activity clinical guidelines for adolescents with type 1 diabetes state 'Children and adolescents should limit the amount of time spent being sedentary, particularly the amount of recreational screen time', with no other sedentary-behaviour-specific recommendations [6]. If the communication of sedentary behaviours' importance has not already been translated to adolescents with type 1 diabetes, then perhaps a 24-h MB approach highlighting the importance of a healthy balance of each behaviour will reframe sedentary behaviours' importance and facilitate optimal health outcomes.

Adolescents frequently discussed how a balance of behaviours aligning with 24-h MB recommendations could benefit their mental health, which is consistent with previous research in adolescents [34]. Specifically, discussions surrounding how all three behaviours impacted motivation and fatigue were prevalent. Motivation and fatigue can have a profound impact on the ability of a person to exert effort or complete tasks [35], which is of great significance to adolescents with type 1 diabetes as they are consistently required to conduct daily self-management activities. Although research has previously highlighted the negative impact that poor sleep can have on self-management activities [36], our research suggests physical activity and sedentary behaviour should also be considered alongside sleep to optimise self-management activities and mental health.

Throughout discussions, the caregivers and school environment were consistently referred to in relation to adolescents' movement behaviours. Adolescents discussed how their caregivers' behaviour, specifically in relation to sleep, was often influenced by their own type 1 diabetes management requirements (e.g., sleep disruptions due to alarms) [37]. Considering the crucial role of caregivers in supporting adolescents living with type 1 diabetes with their everyday management decisions and behaviours, particularly younger adolescents with lower autonomy, it is important that interventions aimed at promoting a healthier balance of movement behaviours also consider the caregivers' behaviours [38]. Research is beginning to investigate interventions aimed at promoting healthier movement behaviours in schools, using activities to improve movement behaviour knowledge [39,40].

Such an intervention might be adapted to cater to adolescents with type 1 diabetes, with a focus on information promoting the importance of reduced sedentary behaviour, assigning active homework and limiting the amount of homework assigned [41] and flexibility in physical education (PE) involvement, including relevant training for PE staff, the presence of type 1 diabetes emergency first aid kits, and the availability of type 1 diabetes 'safe spaces' to complete management activities [42].

Although there are many strengths of this research, including a focus on the adolescents' perspective, facilitation of strong interviewer–participant rapport, and rigorous thematic analysis conducted by trained researchers, there are some limitations. Firstly, the small sample size (n = 15) and predominantly white British participants limit the generalisability of the findings. The homogeneity of the sample may not reflect the diverse experiences of adolescents from different ethnic and socioeconomic backgrounds. Additionally, most participants had access to advanced diabetes management technologies, which could influence their perceptions of movement behaviours and may not be representative of the broader type 1 diabetes adolescent population. Secondly, the participants' prior movement behaviour habits might have shaped their perceptions and ability to reflect on physical activity, sleep, and sedentary behaviour. Given that participants had recently completed a study involving accelerometer-based movement behaviour measurements, they may have been more attuned to certain behaviours. Finally, the study involved interviews exclusively with adolescents. Younger adolescents might struggle to articulate their thoughts, potentially impacting the depth of the data. Future research should consider larger, more diverse samples and include perspectives from caregivers and healthcare providers to enhance the robustness and applicability of the findings.

5. Conclusions

This study highlights the awareness of adolescents with type 1 diabetes regarding the interconnectedness of movement behaviours and the positive influence a balanced approach can have on physical and mental health. The findings provide important information for future interventions to promote holistic movement behaviour interventions for type 1 diabetes management that target the adolescent, their school environment, and their caregivers.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/ijerph22081295/s1, Supplement S1: Accelerometer data processing information and rationale [43–50]; Supplement S2: Adolescent semi-structured interview guide.

Author Contributions: Conceptualization, M.P.; Methodology, M.P., A.K., X.J. and M.C.; Validation, A.K., X.J. and M.C.; Formal analysis, M.P.; Data curation, M.P. and J.S.; Writing—original draft, M.P.; Writing—review & editing, A.K., X.J. and M.C.; Supervision, A.K., X.J. and M.C.; Project administration, M.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The University of Strathclyde Research Ethics Committee reviewed and approved this research (UEC22/04) on 27 April 2022.

Informed Consent Statement: Participants provided consent to conduct and publish the study. For adolescents aged 11–15 years (younger adolescents), written consent was obtained and a verbal consent meeting was conducted with the adolescent and their caregiver to gain verbal consent/assent. For adolescents aged 16–18 years (older adolescents), written consent was obtained.

Data Availability Statement: Data is available upon request to the corresponding author.

Conflicts of Interest: M.C. is a consultant for Signfier Medical Technologies but this activity is not related to the content of this article. The remaining authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

PA	Physical Activity
MVPA	Moderate-to-Vigorous Physical Activity
SB	Sedentary Behaviour
24-h MB	24-Hour Movement Behaviour
T1D	Type 1 Diabetes

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13. Chapter summary

Chapter five summarised the qualitative study completed for this thesis aiming to understand the lived experiences and perspectives of adolescents living with T1D towards 24-h MBs. The findings indicated adolescents with T1D are aware of the interconnectedness of each movement behaviour and the positive influence a balanced approach can have on mood and T1D management. The findings produced from this study provides important contextual information that can be utilised to inform future interventions incorporating the adolescents, their school environment and their caregivers.

The following and final chapter of this thesis will summarise the findings of the three studies against the Medical Research Council (MRC) and National Institute for Health Research (NIHR) frameworks for developing and evaluating complex interventions to better understand next stages of development.

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Chapter 6 – Discussion of Thesis

1. Chapter overview

The aim of this final chapter is to summarise the findings of the three studies conducted as part of this thesis and to discuss how these findings might inform future research and practice. Initially, the main findings from each manuscript are summarised and discussed in relation to the overarching aims of the thesis. Following this, the research produced for this thesis will be positioned within the Medical Research Council (MRC) and National Institute for Health Research (NIHR) frameworks for developing and evaluating complex interventions to better understand next stages of development. Strengths and limitations of the thesis will be highlighted before final conclusions of the thesis are discussed.

2. Summary of findings

The overall aim of this thesis was to explore the feasibility of a 24-h MB approach in adolescents living with T1D. This was conducted by initially completing a systematic review (study 1) to identify the conceptual and empirical gaps within the existing literature. Following this, a quantitative study (study 2) was conducted by objectively measuring free living 24-h MB in adolescents living with T1D to identify behavioural levels and compare those to existing recommendations. Finally, a qualitative study (study 3) was conducted to better understand the perceptions of adolescents living with T1Ds towards a 24-h MB approach and the key factors that affect behavioural engagement.

2.1 Systematic review (study 1)

The systematic review findings highlighted the relationship between 24-h MBs and important T1D outcomes in adolescents. Specifically, that PA shows a favourable association with glycaemic control while SB and sleep is less conclusive. Importantly, this study highlighted that at the time no studies, quantitative or qualitative, considered PA, SB and sleep together as part of a 24-h MB paradigm. This systematic review established the need for the second and third study in this thesis. A quantitative study utilising suitable methods to measure the 24-h MBs of adolescents living with T1D and a qualitative study to understand the perceptions of adolescents living with T1D towards a 24-h MB approach.

2.2 Quantitative study (study 2)

The quantitative study explored free-living levels of PA, SB and sleep using wrist-worn accelerometery and applied validated, reproducible processing methods that align with a 24-h MB approach. This study highlighted adolescents living with T1D had low MVPA levels, high SB levels and a suboptimal sleep duration with few participants meeting either the PA or sleep recommendations for health. While associations with HbA1c and HRQoL were non-significant, associations were in the predicted direction, which overlaps with research highlighting the *potential* benefit from increased MVPA and sleep duration. This study provided empirical evidence of behavioural imbalances within adolescents living with T1D and a robust methodological benchmark for future studies investigating a 24-h MBs in this population.

2.3 Qualitative study (study 3)

The qualitative study explored the perceptions of adolescents living with T1D towards a 24-h MB approach. Adolescents discussed the relationship between mood, glycaemic control and 24-h MBs and the importance of school and caregivers in participating in these behaviours. These insights contextualised and facilitated the explanation of quantitative patterns but importantly, the findings revealed adolescents understood that each of these movement behaviours interact and impact one another which is the key premise of a 24-h MB approach.

3. Positioning within the MRC and NIHR framework

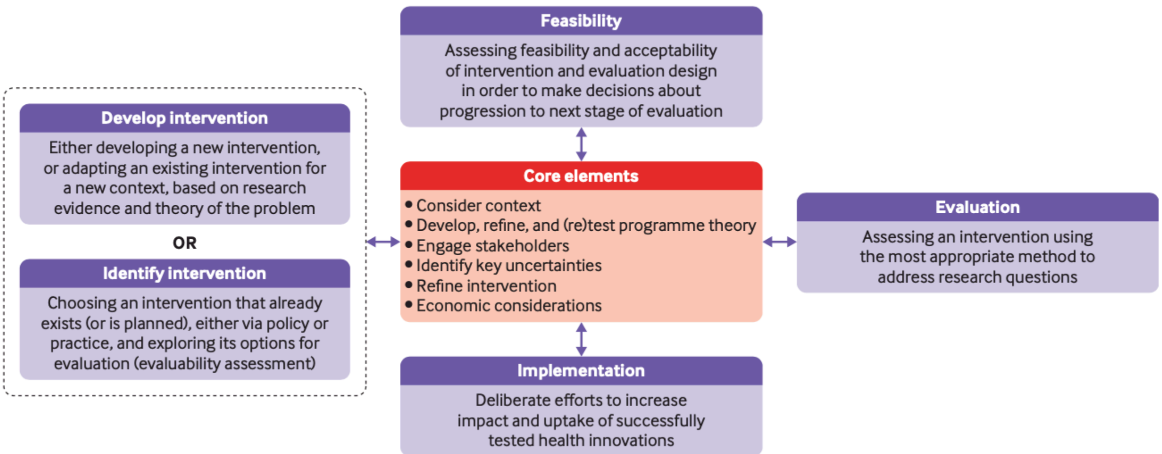
Although this thesis did not develop a specific 24-h MB intervention it provides important evidence that informs the identification of pre-existing interventions and how these might be explored. The research presented in this thesis has generated foundational insights into how a 24-h MB approach might be understood and applied in adolescents living with T1Ds. Positioned within the development phase of the MRC/NIHR framework for complex interventions, the next step is to progress toward feasibility testing and co-design, guided by the programme theory, contextual understanding, and stakeholder input already established.

The MRC/NIHR framework is utilised for developing and evaluating complex interventions, was commissioned jointly by MRC and NIHR and has replaced the previous and widely used MRC guidance (Skivington et al., 2024). This new framework takes into consideration the recent developments in theory and methods. Additionally, it highlights the need to maximise the efficiency, use and impact of research.

Complex intervention development research asks a broad range of questions that go beyond whether an intervention is effective in achieving its intended outcomes (e.g., identifying what other impact it has, considering how it interacts with the context in which it is implemented and how the evidence can be used in real world decision making). Complex intervention research can be considered in specific non-sequential phases, specifically, development or identification of an intervention; feasibility of the intervention; implementation of the intervention and evaluation of the intervention. Importantly, at each of these phases six core questions should be considered and the answers to these questions should be utilised to determine if the research should proceed to the next phase, return to a previous phase, repeat a phase or stop (**Figure 6.1**). These questions include:

- How does the intervention interact with its context?
- What is the underpinning programme theory?
- How can diverse stakeholder perspectives be included in the research?
- What are the key uncertainties?
- How can the intervention be refined?
- What are the comparative resource and outcome consequences of the intervention?

Figure 6.1: MRC and NIHR framework for developing complex interventions (Skivington, 2024).



Each of the six key phases within this framework have been discussed below in relation to the findings from this thesis. Through the research conducted for this thesis a programme theory has been established, contextual influences defined, and key stakeholders have been engaged. The next steps include the refinement of existing 24-h MB interventions, so they are specific to adolescents living with T1D.

This should be done through co-design and piloting with relevant stakeholders (i.e., adolescents living with T1D and their caregivers) to assess feasibility and acceptability.

3.1 Consider context

The context in which complex interventions are implemented can impact their overall effectiveness. An intervention might be effective in one environment and ineffective or even harmful in another (i.e. clinic vs school setting). The findings from this thesis, particularly from the qualitative study, highlighted that 24-h MBs for adolescents living with T1D are shaped strongly by school routines and caregiver involvement.

3.2 Develop, refine and (re)test programme theory

Programme theory identifies key components, mechanisms of action and how these interact with context. Programme theory is ideally co-developed at the beginning of complex intervention development and continuously refined throughout the research process. Importantly, this theory will align key stakeholders, clarify uncertainties and guide evaluation. The findings from this thesis provides a solid foundation of programme theory that can be refined alongside future research development. Specifically, that both the literature and clinical guidance within this population has historically focused on the examination of movement behaviours in isolation, that adolescents living with T1D currently do not obtain recommended levels of movement behaviours and that 24-h MB interventions may be more effective and meaningful for adolescents with T1D than single behaviour approaches.

3.3 Engage stakeholders

Stakeholders are those who are affected by, delivering or involved in the complex intervention (i.e., adolescents with T1D, caregivers, schools, clinicians etc). Ensuring engagement with a diverse range of stakeholders improves intervention relevance, co-development of programme theory and impact on policy and practice. The purpose of stakeholder engagement depends on the context and phase of research. This research is still in its infancy and therefore, targeting the key stakeholder, adolescents with T1D, who have lived experience was paramount. Although adolescents' insights will inform research next steps, future research might revisit this phase to understand other key stakeholders perceptions towards a 24-h MB approach. Specifically, targeting stakeholders related to the context in which a 24-h MB intervention might be implemented (i.e., caregivers and school staff).

3.4 Identify key uncertainties

A flexible and evolving approach must be adopted alongside complex intervention research. Key uncertainties from existing evidence and through stakeholder input should be considered. This is particularly relevant when interventions are conducted in real-world settings where researchers have less control of additional factors. Although the findings in this thesis highlight preliminary uncertainties of a 24-h MB (i.e., how best to measure MBs in adolescents and how best to implement a 24-h MB intervention in relation to its identified context) future research should investigate uncertainties of a 24-h MB interventions through key stakeholder input (i.e., caregivers, school staff).

3.5 Refine intervention

Refining the intervention is crucial throughout the research phases and is particularly essential during the development and feasibility stages where interventions must adapt to context, emerging findings and key stakeholders**.** The findings from this thesis suggested a school-based intervention targeting 24-h MBs would be an appropriate intervention for this population. A range of school based 24-h MB interventions have been tested across different age groups.

A recent systematic review conducted by Rodrigo-Sanjoaquín, Tapia-Serrano, López-Gil, and Sevil-Serrano (2025) examined the effects of school-based interventions promoting all 24-h MBs in preschoolers, children and adolescents. Overall, they reported interventions reduced SB-related outcomes, particularly screen time, and increased sleep duration although effects were small. However, the interventions did not increase PA levels (i.e., total PA and MVPA), highlighting the difficulties in modifying PA within the school environment and suggested that LPA should also be measured. Importantly, this systematic review highlighted the lack of school-based interventions targeting all three movement behaviours despite the 24-h MB approach being in place for almost a decade.

From the seven randomised controlled trials (RCTs) that were included in this review, four studies were conducted in the age group investigated in this thesis (11–18 years). Champion et al. (2023) 'Health4Life' intervention targeted Australian adolescents (12–14 years, n=6640) using a multi-component school-based programme utilising online cartoon modules co-designed by adolescents and informed by social influence to provide education about smoking, alcohol, diet, PA, SB and sleep. Alongside the cartoons it utilised engaging web-based, targeted feedback about the national health guidelines and optional online and teacher-delivered activities aimed to reinforce learning. Participants in this study utilised a smartphone app for self-monitoring, goal setting and motivational purposes (i.e., badges or rewards). Donnelly, Buchan, McLellan, Roberts, and Arthur (2023) utilised the ‘Happy Homework’ intervention to target Scottish adolescents (9–12 years, n=128) PA, SB, sleep and diet. The intervention used homework activities for the parent and child, which were co-developed with educators and piloted by families. The homework activities were informed by principles of self-determination theory (SDT) and aimed to provide education on behavioural guidelines. To facilitate adherence and motivation, happy face stickers were placed on the workbooks as a small reward. Pablos, Nebot, Vañó-Vicent, Ceca, and Elvira (2018) utilised the ‘Healthy Habits Program’ to target Spanish adolescents (10–12 years, n=158) health behaviours including PA, SB and sleep. The intervention combined PA sessions, educational discussions and home-based family materials. Sevil, García-González, Abós, Generelo, and Aibar (2019) ‘Paths of the Pyrenees’ intervention aimed to empower Spanish adolescents (12–14 years, n=210) to develop health literacy and responsibility of healthier behaviours including PA, SB and sleep. This intervention used a multi-component school-based approach to target the wider school community by combining academic learning, teacher development, family involvement and extracurricular activities.

Although current 24-h MB interventions have not been developed specifically for adolescents living with T1D they offer a valuable foundation for adaptation. These interventions can serve as practical templates for future work, particularly when co-designed with key stakeholders (i.e., adolescents with T1D, caregivers, and educators) to ensure relevance, acceptability, and feasibility. Adapting existing models in this way not only supports contextual tailoring but also strengthens the likelihood of successful implementation and sustainability.

3.6 Economic considerations

Conducting a comparative analysis of costs (i.e., resource use) and consequences (i.e., outcomes) for all potential courses of action is core to intervention research. To conduct an economic evaluation for complex interventions, cost benefit analysis or cost consequence analysis approaches might be used as they account for health and non-health impacts across the sectors. These economic frameworks can provide a comprehensive and policy relevant understanding of the intervention value. This phase in the framework has not yet been addressed and economic considerations need planning in future feasibility and pilot work.

4. Future research aligned with the framework

After evaluating the findings from this thesis against the MRC/NIHR framework for the development of complex health interventions, it is recommended that future research should stay within the development phase of the framework. The logical next step is to design and pilot an intervention based on the emerging programme theory generated from this thesis. The findings from this thesis suggest a school-based intervention targeting PA, SB and sleep which incorporates both the adolescent, and their caregivers would be appropriate. This intervention might take inspiration from existing multi-component 24-h MB school-based interventions (see section 3.2 in this chapter) that includes digital tools (e.g., wearable feedback, smartphone apps), routine-based strategies, and behavioural supports for families and school environments. It is essential that these components are considered in the context of adolescents living with T1D. For example, adolescents with T1D often rely on a smartphone for diabetes management which could leave them feeling singled out or excluded in environments shifting toward smartphone-free policies (e.g., schools) (Gregory & Kar, 2025). Delivering a digital intervention through smartphones could unintentionally amplify this concern. These types of considerations in intervention development are crucial to ensure intervention effectiveness. Age-appropriate tailoring should also be considered, particularly for older adolescents who may require different motivational strategies.

Importantly, this multi-component 24-h MB school-based intervention should be co-designed with adolescents living with T1D to improve acceptability, feasibility and effectiveness of that intervention to support healthy 24-h MBs. Utilising a co-design approach would place the adolescent living with T1D at the centre of intervention design and consider their unique insights and knowledge. To strengthen this intervention, caregivers and school systems might also be considered in the co-design process due to their influence in adolescents movement behaviours that were highlighted from the qualitative study in this thesis.

Although economic evaluation has not yet been addressed in this research, future feasibility and pilot work should integrate early economic thinking. Cost tracking tools, scalability considerations, and delivery models should be embedded from the outset. Broader economic frameworks such as cost consequence analysis may be especially useful given the potential cross-sectoral benefits (e.g., education, health, family wellbeing) (Hartfiel & Edwards, 2019).

Planning for a robust evaluation phase will involve defining clear feasibility outcomes (i.e., recruitment, engagement, adherence, and acceptability). A mixed-methods approach will be critical to not only assess preliminary efficacy but also identify barriers to implementation, contextual adaptations, and mechanisms of action. This ensures that future trial work captures both "what works" and "how and why it works," in line with the framework’s emphasis on real-world relevance.

5. Strengths and limitations

This PhD had several important strengths. To the author's knowledge, this is one of the first projects to apply a 24-h MB framework specifically to adolescents living with T1D. The systematic review provided a comprehensive overview of both quantitative and qualitative 24-h MB literature in adolescents living with T1D. Additionally, this systematic review included a meta-analysis to better understand the relationships between 24-h MBs and important diabetes related outcomes that are known to contribute to adolescents' ability to adapt to the condition.

Data collection for the quantitative and qualitative study was conducted with cultural sensitivity and ethical rigour, including careful recruitment procedures for engaging a vulnerable adolescent population online. The development of an online recruitment strategy grounded in marketing and health communication frameworks (i.e., AIDA and ACME) represents a further strength, offering a replicable model for future researchers seeking to engage this population. The quantitative study utilised wrist-worn research grade accelerometer data that used validated, reproducible wear-time criteria and algorithms aligned with emerging best practice in 24-h MB research and provide a robust benchmark for future studies in the field. The qualitative study placed focus primarily on adolescents living with T1D, by conducting semi-structured interviews with adolescents only, which removed influencing perspectives and further strengthened the finding that adolescents recognised key premises of the 24-h MB paradigm, understanding their interconnected nature. Moreover, this PhD contributes conceptually to a preliminary programme theory and begins to map findings onto the updated MRC and NIHR framework for complex interventions. In doing so, it has laid a strong foundation for future co-designed intervention development in this area.

There are also limitations to acknowledge. The quantitative study component involved a relatively small sample size, which may limit the generalisability of the findings. While high-quality accelerometery methods were employed, the analysis did not incorporate compositional data analysis (CoDA) which is recommended for appropriately modelling the co-dependent nature of movement behaviours across the 24-hour day. CoDA was not possible for this thesis due to a sample size that did not support this type of analysis. Additionally, the cross-sectional design limits any causal inference between movement behaviours and outcomes such as glycaemic control or health-related quality of life (HRQoL). Another limitation relates to the sample composition. Although this research provided important initial insights, participant diversity was limited, reducing the broader applicability of the findings. Future work should prioritise inclusive recruitment strategies to ensure the needs of diverse adolescent populations are better represented. Finally, as data collection was conducted entirely online, formal clinical verification of T1D diagnosis was not feasible, particularly for participants aged sixteen years and over who could self-consent. While eligibility screening and study specific recruitment strategies channels were used to target individuals living with T1D, the potential for self-report misclassification cannot be entirely excluded and should be considered a limitation.

Overall, this thesis provides a valuable and original contribution to the understanding of 24-h MBs in adolescents living with T1D. While there are limitations to the current work, the findings offer a solid platform for future feasibility testing, co-design, and intervention refinement in line with the MRC/NIHR framework.

6. Conclusions

Overall, this PhD has provided novel insight into the feasibility of a 24-h MB approach in adolescents living with T1D. This was achieved by conducting a comprehensive systematic review and meta-analysis of both quantitative and qualitative studies; deployment of research grade wrist-worn accelerometery aligning with 24-h MB collection and processing best practice and semi-structured qualitative interviews focusing solely on adolescents living with T1Ds perspective towards 24-h MBs. This work lays the foundation for future co-designed 24-h MB interventions that aim to promote a healthy balance of all movement behaviours, rather than targeting behaviours in isolation.

Chapter 6 References

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List of Appendices

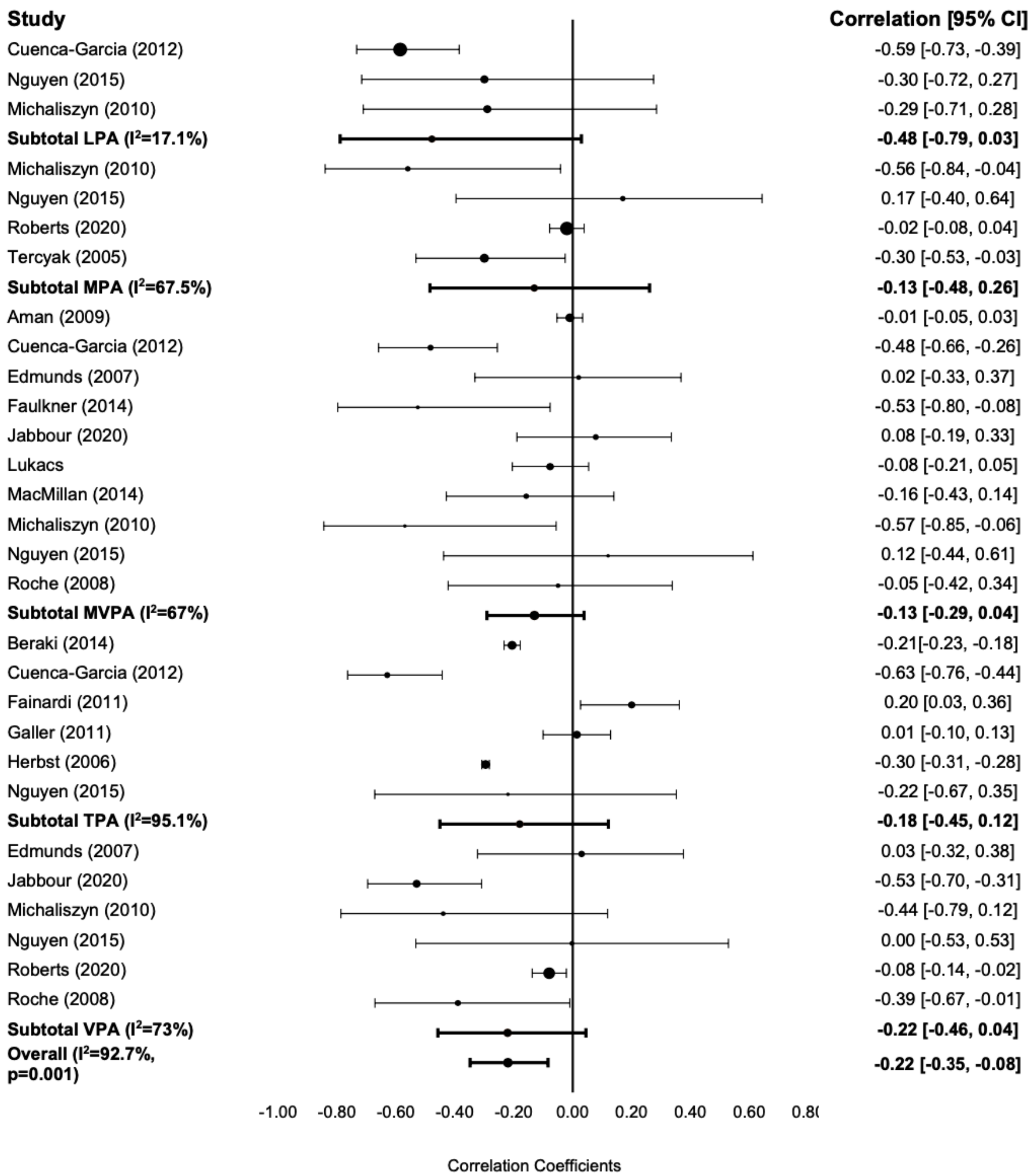
Appendix Q: Study Three, Qualitative (Supplementary Materials 1), Accelerometer Data Processing Information and Rationale

Appendix R: Study Three, Qualitative (Supplementary Materials 2), Adolescent Semi-structured Interview Guide

Appendix S: Study Three, Qualitative (Supplementary Materials 3), Codebook of Themes

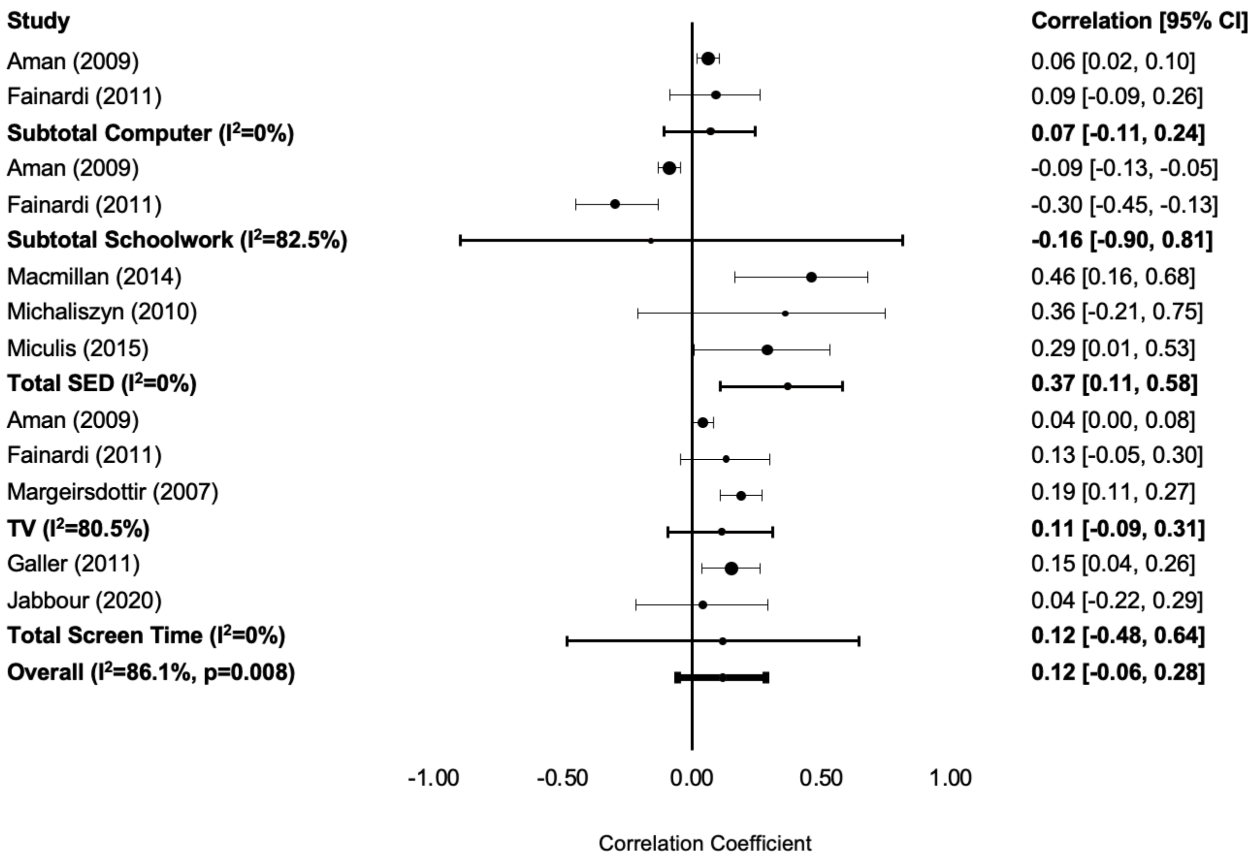
Appendix A: Study One (Figure S1), Forest Plot of Physical Activity Individual Studies.

CI, confidence interval; LPA, light physical activity; MPA, moderate physical activity; MVPA, moderate-vigorous physical activity; TPA, total physical activity; VPA, vigorous physical activity; I2, statistic of heterogeneity



Appendix B: Study One (Figure S2), Forest Plot of Sedentary Behaviour Individual Studies.

CI, confidence interval; I^2, statistic of heterogeneity.



Appendix C: Study One (Supplementary Materials S1), Glossary of Terms.

Glossary of Sleep Health Terms

Sleep duration: The total amount of sleep obtained per 24 hours.
Sleep continuity or efficiency: The ease of falling asleep and returning to sleep.

Timing: The placement of sleep within the 24-hour day.
Alertness/sleepiness: The ability to maintain attentive wakefulness.
Satisfaction/Quality: The subjective assessment of "good" or "poor" sleep.

Glossary of Primary Outcomes

HbA1c - measures the average level of blood glucose over the past 2-3 months to indicate long-term glycaemic control.
CGM Metrics - standardised metrics and targets to guide clinicians, patients and researchers in using, analysing, and reporting CGM data to comprehensively assess glycaemic control:

1) Number of days CGM worn
2) Percentage of time CGM is active
3) Mean glucose
4) Estimated A1C
5) Glycaemic variability (%Coefficient Variation or Standard Deviation)
6) Time Above Range (Level 2)
7) Time Above Range (Level 1)
8) Time In Range
9) Time Below Range
10) Time Below Range
11) Low Blood Glucose Indicator and High Blood Glucose Indicator (risk indices)
12) Episodes (hypoglycaemia and hyperglycaemia)
13) Area under the curve
14) Time blocks (24-h, day, night)

Quality of Life - the extent to which a person obtains satisfaction from life. The following are important for a good quality of life: emotional, material, and physical well-being; engagement in interpersonal relations; opportunities for personal (e.g., skill) development; exercising rights and making self-determining lifestyle choices; and participation in society[3]:

1) *Health-Related Quality of Life* - an individual's or a group's perceived physical and mental health over time.
2) *Diabetic Quality of Life* – health related quality of life specific to diabetic population.

Glossary of Secondary Outcomes

Depression - a negative affective state, ranging from unhappiness and discontent to an extreme feeling of sadness, pessimism, and despondency, that interferes with daily life.
Anxiety - an emotion characterized by apprehension and somatic symptoms of tension in which an individual anticipates impending danger, catastrophe, or misfortune.
Stress - the physiological or psychological response to internal or external stressors. Stress involves changes affecting nearly every system of the body, influencing how people feel and behave.
Distress - the negative stress response, often involving negative affect and physiological reactivity: a type of stress that results from being overwhelmed by demands, losses, or perceived threats.
Self-Management - an individual's control of his or her behaviour, particularly regarding the pursuit of a specific objective (e.g., weight loss).
Social Competence - effectiveness or skill in interpersonal relations and social situations, increasingly considered an important component of mental health. Social competence involves the ability to evaluate social situations and determine what is expected or required; to recognize the feelings and intentions of others; and to select social behaviours that are most appropriate for that given context.
Coping - the use of cognitive and behavioural strategies to manage the demands of a situation when these are appraised as taxing or exceeding one's resources or to reduce the negative emotions and conflict caused by stress.
Family Functioning - the social and structural properties of the global family environment, specifically family interactions/relationships (e.g., family conflict, cohesion, adaptability, organisation and quality of communication).

Appendix D: Study One (Supplementary Materials S2), Search Strategy.

An electronic literature search was conducted on **07/05/2021** in the following electronic databases: MEDLINE (Ovid), EMBASE (Ovid), Web of Science (Core Collection), APAPsycINFO (EBSCOhost), SPORTDiscus (EBSCOhost), Applied Social Sciences Index and Abstracts (ProQuest), Sports Medicine & Education Index (ProQuest) Wiley Cochrane Library, OpenGrey and Open Dissertations (EBSCOhost).

For each database, a search strategy consisting of keywords and synonyms was developed using the PICO (Population, Intervention/Exposure, Comparison and Outcome) and SPIDER (Sample, Phenomenon of Interest, Design, Evaluation and Research type) frameworks.

Some of the outcomes searched for this review were very specific and not available as a subject term or related narrower term in databases-controlled vocabulary (e.g. the continuous glucose monitor metrics of interest). Therefore, all developed keywords and synonyms were included in each search and combined using the “AND” and “OR” boolean operators. Additionally, the use of “wildcards” were used to enhance the searches.

Then to ensure complete comprehensiveness of the search, identified keywords for this systematic review were searched for in the controlled vocabulary of each database and specific database functions/tools were utilised, if available. For example, in MEDLINE and EMBASE (Ovid Platform), the key term “Type 1 Diabetes” was “mapped” to match terms with the databases-controlled vocabulary. This returned the subject headings “Diabetes Mellitus, Type 1” and “insulin dependent diabetes mellitus,” respectively. These terms were then “exploded” (exp) to retrieve results containing the subject heading in combination with all of its narrower, more specific subheadings.

A summary of the keywords and their combinations used for each database search is highlighted below:

1. Type 1 Diabetes
2. Adolescent
3. Physical Activity
4. Sedentary Behaviour
5. Sleep
6. 24-hour Movement Behaviour
7. Health Behaviour or Health Knowledge or Health Attitude or Health Practice (*Broader Variety of Phrases to Comprehensively Incorporate both Qualitative and Quantitative Studies*)
8. HbA1c, CGM Metrics and Quality of Life
9. Depressive Symptoms, Anxiety, Stress, Self-Management, Coping, Self-Efficacy, Family Functioning and Social Competence
10. 1 and 2 (*Population/Sample*)
11. 3 or 4 or 5 or 6 or 7 (*Intervention/Exposure/Phenomenon of Interest*)
12. 8 or 9 (*Primary and Secondary Outcomes*)
13. 10 and 11 and 12 (*Results*)

Web of Science (1,418 results) – Core Collection

Notes:

Topic (TS) search field selected

#1 TS=(“Type 1 Diabetes” OR “insulin-dependent diabetes” OR T1DM OR IDDM OR “type 1” OR “type I” OR “juvenile onset diabetes” OR “child onset diabetes”)

#2 TS=(adolescent* OR youth* OR juvenile* OR teen* OR “young adult*” OR “young people” OR minor* OR pubescent* OR “emerging adult*”)

#3 TS=(“physical* activ*” OR exercis* OR “moderate intensity” OR “light intensity” OR “vigorous intensity” OR “very vigorous intensity” OR “high intensity” OR workout OR “physical training” OR sport* OR “strength training” OR “strength activit*” OR “resistance training” OR “resistance activit*” OR “aerobic training” OR “aerobic activit*” OR “anaerobic training” OR “anaerobic activit*” OR “flexibility training” OR “flexibility activit*” OR “endurance training” OR “endurance activit*” OR “physical education” OR PE OR walking)

#4 TS=(“sedentary behav*” OR sit* OR “screen time” OR sedentary)

#5 TS=(sleep* OR alertness OR wakefulness)

#6 TS=("24-hour movement behav*" OR "integrated behav*")

#7 TS=(“health behav*” OR “health knowledge” OR “health attitude*” OR “health practice*”)

#8 TS=(HbA1c OR A1c OR “glyc* h$emoglobin” OR glycoh$emoglobin OR “glyc$emic control” OR “glucose control” OR “h$emoglobin A1c” OR “mean glucose” OR “mean daily glucose” OR hypoglyc$emia OR hyperglyc$emia OR “time in hypoglyc$emic range” OR “time in level 1 hypoglyc$emic range” OR “time in level 2 hypoglyc$emic range” OR “time below range” OR TBR OR “time in target range” OR “time in range” OR TIR OR “time in hyperglyc$emic range” OR “time in level 1 hyperglyc$emic range” OR “time in level 2 hyperglyc$emic range” OR TAR OR “glucose variability” OR “glyc$emic variability” OR “estimated A1c” OR eA1C OR “glucose management indicator” OR GMI OR “hypoglyc$emic episodes” OR “hyperglyc$emic episodes” OR “area under the curve” OR AUC OR “risk of hypoglyc$emia” OR LBGI OR “risk of hyperglyc$emia” OR HBGI OR “time blocks” OR “quality of life” OR QoL OR well-being)

#9 TS=(depress* OR anxiet* OR stress* OR distress* OR self-management OR self-care OR self-regulations OR self-monitoring OR *adherence OR *compliance OR cope OR coping OR resilien* OR self-efficacy OR “behavioural control” OR confidence OR self-esteem OR “family functioning” OR “family conflict” OR “family cohesion” OR “family flexibility” OR “family relation*” OR “family communication” OR “family problem solving” OR “family support” OR “family responsibility” OR “parental involvement” OR “family environment” OR “family adaptability” OR “social competence” OR “social skills” OR “social development” OR “social communication”)

#9 #1 and #2

#10 #3 or #4 or #5 or #6 or #7

#11 #8 or #9

#12 #10 and #11 and #12

MEDLINE (3,550 results) – Ovid Platform

Notes:

Keyword search was selected

Abstract (.ab) search field selected

"Mapping" and "Exploding" to *all* subheadings were applied for keywords of interest available in the database.

1 (Type 1 Diabetes or insulin dependent diabetes or T1DM or IDDM or type 1 or type I or juvenile onset diabetes or child onset diabetes).ab. or exp Diabetes Mellitus, Type 1/

2 (adolescent* or youth* or juvenile* or teen* or young adult* or young people or minor* or pubescent or emerging adult*).ab. or exp Adolescent/ or exp Young Adult/ or exp Minors/

3 (physical* activ* or exercis* or moderate intensity or light intensity or vigorous intensity or very vigorous intensity or high intensity or workout or physical training or sport* or strength training or strength activit* or resistance training or resistance activit* or aerobic training or aerobic activit* or anaerobic training or anaerobic activit* or flexibility training or flexibility activit* or endurance training or endurance activit* or physical education or PE or walking).ab. or exp Exercise/

4 (sedentary behav* or sit* or screen time or sedentary).ab or exp Sedentary Behavior/

5 (sleep* or alertness or wakefulness).ab. or exp Sleep/

6 (24-hour movement behav* or integrated behav*).ab.

7 (health behav* or health knowledge or health attitude* or health practice*).ab or exp Health Behavior/ or exp Health Knowledge, Attitudes, Practice/ or exp Attitude to Health/

8 (HbA1c or A1c or glyc* h?emoglobin or glycoh?emoglobin or glyc?emic control or glucose control or h?emoglobin A1c or mean glucose or mean daily glucose or hypoglyc?emia or hyperglyc?emia or hypoglyc?emic range or time below range or TBR or time in range or TIR or hyperglyc?emic range or TAR or glucose variability or glyc?emic variability or estimated A1c or eA1C or glucose management indicator or GMI or hypoglyc?emic episodes or hyperglyc?emic episodes or area under the curve or AUC or risk of hypoglyc?emia or LBGI or risk of hyperglyc?emia or HBGI or time blocks or quality of life or QoL or well-being).ab or exp Glycated Hemoglobin A/ or exp Quality of Life/ or exp Blood Glucose/ or exp Hypoglycemia/ or exp Hyperglycemia/

9 (depress* or anxiet* or stress* or distress* or self-management or self-care or self-regulations or self-monitoring or adherence or compliance or cope or coping or resilien* or self-efficacy or behavioural control or confidence or self-esteem or family functioning or family conflict or family cohesion or family flexibility or family relation* or family communication or family problem solving or family support or family responsibility or parental involvement or family environment or family adaptability or social competence or social skills or social development or social communication).ab or exp Depression/ or exp Anxiety/ or exp Stress, Psychological/ or exp Psychological Distress/ or exp Self-Management/ or exp Medication Adherence/ or exp Self Care/ or exp Self Efficacy/ or exp Family Relations/ or exp Social Skills/ or exp Adaptation, Psychological/

10 1 and 2

11 3 or 4 or 5 or 6 or 7

12 8 or 9

13 10 and 11 and 12

EMBASE (3,232 results) – Ovid Platform

Notes:

Keyword search was selected

Abstract (.ab.) search field selected

“Mapping” and “Exploding” to *all* subheadings were applied for keywords of interest available in the database.

1 (Type 1 Diabetes or insulin dependent diabetes or T1DM or IDDM or type 1 or type I or juvenile onset diabetes or child onset diabetes).ab. or exp insulin dependent diabetes mellitus/

2 (adolescent* or youth* or juvenile* or teen* or young adult* or young people or minor* or pubescent or emerging adult*).ab. or exp adolescent/

3 (physical* activ* or exercis* or moderate intensity or light intensity or vigorous intensity or very vigorous intensity or high intensity or workout or physical training or sport* or strength training or strength activit* or resistance training or resistance activit* or aerobic training or aerobic activit* or anaerobic training or anaerobic activit* or flexibility training or flexibility activit* or endurance training or endurance activit* or physical education or PE or walking).ab or exp physical activity/

4 (sedentary behav* or sit* or screen time or sedentary).ab. or exp sedentary time/ or exp sedentary lifestyle/

5 (sleep* or alertness or wakefulness).ab. or exp sleep/

6 (24-hour movement behav* or integrated behav*).ab.

7 (health behav* or health knowledge or health attitude* or health practice*).ab. or exp health behavior/ or exp attitude to health/

8 (HbA1c or A1c or glyc* h?emoglobin or glycoh?emoglobin or glyc?emic control or glucose control or h?emoglobin A1c or mean glucose or mean daily glucose or hypoglyc?emia or hyperglyc?emia or hypoglyc?emic range or time below range or TBR or time in range or TIR or hyperglyc?emic range or TAR or glucose variability or glyc?emic variability or estimated A1c or eA1C or glucose management indicator or GMI or hypoglyc?emic episodes or hyperglyc?emic episodes or area under the curve or AUC or risk of hypoglyc?emia or LBGI or risk of hyperglyc?emia or HBGI or time blocks or quality of life or QoL or well-being).ab. or exp hemoglobin A1c/ or exp quality of life/ or exp glucose blood level/

9 (depress* or anxiet* or stress* or distress* or self-management or self-care or self-regulations or self-monitoring or adherence or compliance or cope or coping or resilien* or self-efficacy or behavioural control or confidence or self-esteem or family

functioning or family conflict or family cohesion or family flexibility or family relation* or family communication or family problem solving or family support or family responsibility or parental involvement or family environment or family adaptability or social competence or social skills or social development or social communication).ab. or exp depression/ or exp anxiety/ or exp stress/ or exp distress syndrome/ or exp patient compliance/ or exp self concept/ or exp family relation/ or exp social competence/ or exp coping behavior/

10 1 and 2

11 3 or 4 or 5 or 6 or 7

12 8 or 9

13 10 and 11 and 12

APAPsycInfo (715 results) – EBSCOHost Platform

Notes:

Unqualified Search conducted

'Boolean/Phrase Search Mode' selected for each search

Apply Related Words and Apply Equivalent Subjects 'expanders' applied for each search

S1 ("Type 1 Diabetes" OR "insulin-dependent diabetes" OR T1DM OR IDDM OR "type 1" OR "type I" OR "juvenile onset diabetes" OR "child onset diabetes")

S2 (adolescent* OR youth* OR juvenile* or teen* OR young adult* OR "young people" OR minor* OR pubescent OR "emerging adult*")

S3 ("physical* activ*" OR exercis* OR "moderate intensity" OR "light intensity" OR "vigorous intensity" OR "very vigorous intensity" OR "high intensity" OR workout OR "physical training" OR sport* OR "strength training" OR "strength activit*" OR "resistance training" OR "resistance activit*" OR "aerobic training" OR "aerobic activit*" OR "anaerobic training" OR "anaerobic activit*" OR "flexibility training" OR "flexibility activit*" OR "endurance training" OR "endurance activit*" OR "physical education" OR PE OR walking)

S4 ("sedentary behav*" OR sit* OR "screen time" OR sedentary)

S5 (sleep* OR alertness OR wakefulness)

S6 ("24-hour movement behav*" OR "integrated behav*")

S7 ("health behav*" or "health knowledge" or "health attitude*" or "health practice*")

S8 (HbA1c OR A1c OR "glyc* h#emoglobin" OR glycoh#emoglobin OR "glyc#emic control" or "glucose control" or "h#emoglobin A1c" OR "mean glucose" OR "mean daily glucose" OR hypoglyc#emia OR hyperglyc#emia OR "time in hypoglyc#emic range" OR "time in level 1 hypoglyc#emic range" OR "time in level 2 hypoglyc#emic range" OR "time below range" OR TBR OR "time in target range" OR "time in range" OR TIR OR "time in hyperglyc#emic range" OR "time in level 1 hyperglyc#emic range" OR "time in level 2 hyperglyc#emic range" OR TAR OR "glucose variability" OR "glyc#emic variability" OR "estimated A1c" OR eA1C OR "glucose management indicator" OR GMI OR "hypoglyc#emic episodes" OR "hyperglyc#emic episodes" OR "area under the curve" OR AUC OR "risk of hypoglyc#emia" OR LBGI OR "risk of hyperglyc#emia" OR HBGI OR "time blocks" OR "quality of life" OR QoL OR well-being)

S9 (depress* OR anxiet* OR stress* OR distress* OR self-management OR self-care OR self-regulations OR self-monitoring OR adherence OR compliance OR cope OR coping OR resilien* OR self-efficacy OR “behavioural control” OR confidence OR self-esteem OR “family functioning” OR “family conflict” OR “family cohesion” OR “family flexibility” OR “family relation*” OR “family communication” OR “family problem solving” OR “family support” OR “family responsibility” OR “parental involvement” OR “family environment” OR “family adaptability” OR “social competence” OR “social skills” OR “social development” OR “social communication”)

S10 S1 AND S2

S11 S3 OR S4 OR S5 OR S6 OR S7

S12 S8 OR S9

S13 S10 AND S11 AND S12

SPORTDiscus (75 results) - EBSCOHost Platform

Notes:

Unqualified Search conducted

'Boolean/Phrase Search Mode' selected for each search

Apply Related Words and Apply Equivalent Subjects 'expanders' applied for each search

S1 ("Type 1 Diabetes" OR "insulin-dependent diabetes" OR T1DM OR IDDM OR "type 1" OR "type I" OR "juvenile onset diabetes" OR "child onset diabetes")

S2 (adolescent* OR youth* OR juvenile* or teen* OR young adult* OR "young people" OR minor* OR pubescent OR "emerging adult*")

S3 ("physical* activ*" OR exercis* OR "moderate intensity" OR "light intensity" OR "vigorous intensity" OR "very vigorous intensity" OR "high intensity" OR workout OR "physical training" OR sport* OR "strength training" OR "strength activit*" OR "resistance training" OR "resistance activit*" OR "aerobic training" OR "aerobic activit*" OR "anaerobic training" OR "anaerobic activit*" OR "flexibility training" OR "flexibility activit*" OR "endurance training" OR "endurance activit*" OR "physical education" OR walking OR PE)

S4 ("sedentary behav*" OR sit* OR "screen time" OR sedentary)

S5 (sleep* OR alertness OR wakefulness)

S6 ("24-hour movement behav*" OR "integrated behav*")

S7 ("health behav*" OR "health knowledge" OR "health attitude*" OR "health practice*")

S8 (HbA1c OR A1c OR "glyc* h#emoglobin" OR glycoh#emoglobin OR "glyc#emic control" or "glucose control" or "h#emoglobin A1c" OR "mean glucose" OR "mean daily glucose" OR hypoglyc#emia OR hyperglyc#emia OR "time in hypoglyc#emic range" OR "time in level 1 hypoglyc#emic range" OR "time in level 2 hypoglyc#emic range" OR "time below range" OR TBR OR "time in target range" OR "time in range" OR TIR OR "time in hyperglyc#emic range" OR "time in level 1 hyperglyc#emic range" OR "time in level 2 hyperglyc#emic range" OR TAR OR "glucose variability" OR "glyc#emic variability" OR "estimated A1c" OR eA1C OR "glucose management indicator" OR GMI OR "hypoglyc#emic episodes" OR "hyperglyc#emic episodes" OR "area under the curve" OR AUC OR "risk of hypoglyc#emia" OR LBGI OR "risk of hyperglyc#emia" OR HBGI OR "time blocks" OR "quality of life" OR QoL OR well-being)

S9 (depress* OR anxiet* OR stress* OR distress* OR self-management OR self-care OR self-regulations OR self-monitoring OR adherence OR compliance OR cope OR coping OR resilien* OR self-efficacy OR “behavioural control” OR confidence OR self-esteem OR “family functioning” OR “family conflict” OR “family cohesion” OR “family flexibility” OR “family relation*” OR “family communication” OR “family problem solving” OR “family support” OR “family responsibility” OR “parental involvement” OR “family environment” OR “family adaptability” OR “social competence” OR “social skills” OR “social development” OR “social communication”)

S10 S1 AND S2

S11 S3 OR S4 OR S5 OR S6 OR S7

S12 S8 OR S9

S13 S10 AND S11 AND S12

OpenDissertations (Grey Literature; 32 results) - EBSCOHost Platform

Notes:

Unqualified Search conducted

‘Boolean/Phrase Search Mode’ selected for each search

Apply Related Words and Apply Equivalent Subjects ‘expanders’ applied for each search

S1 (“Type 1 Diabetes” OR “insulin-dependent diabetes” OR T1DM OR IDDM OR “type 1” OR “type I” OR “juvenile onset diabetes” OR “child onset diabetes”)

S2 (adolescent* OR youth* OR juvenile* or teen* OR young adult* OR “young people” OR minor* OR pubescent OR “emerging adult*”)

S3 (“physical* activ*” OR exercis* OR “moderate intensity” OR “light intensity” OR “vigorous intensity” OR “very vigorous intensity” OR “high intensity” OR workout OR “physical training” OR sport* OR “strength training” OR “strength activit*” OR “resistance training” OR “resistance activit*” OR “aerobic training” OR “aerobic activit*” OR “anaerobic training” OR “anaerobic activit*” OR “flexibility training” OR “flexibility activit*” OR “endurance training” OR “endurance activit*” OR “physical education” OR walking OR PE)

S4 (“sedentary behav*” OR sit* OR “screen time” OR sedentary)

S5 (sleep* OR alertness OR wakefulness)

S6 (“24-hour movement behav*” OR “integrated behav*”)

S7 (“health behav*” OR “health knowledge” OR “health attitude*” OR “health practice*”)

S8 (HbA1c OR A1c OR “glyc* h#emoglobin” OR glycoh#emoglobin OR “glyc#emic control” or “glucose control” OR “h#emoglobin A1c” OR “mean glucose” OR “mean daily glucose” OR hypoglyc#emia OR hyperglyc#emia OR “time in hypoglyc#emic range” OR “time in level 1 hypoglyc#emic range” OR “time in level 2 hypoglyc#emic range” OR “time below range” OR TBR OR “time in target range” OR “time in range” OR TIR OR “time in hyperglyc#emic range” OR “time in level 1 hyperglyc#emic range” OR “time in level 2 hyperglyc#emic range” OR TAR OR “glucose variability” OR “glyc#emic variability” OR “estimated A1c” OR eA1C OR “glucose management indicator” OR GMI OR “hypoglyc#emic episodes” OR “hyperglyc#emic episodes” OR “area under the curve” OR AUC OR “risk of hypoglyc#emia” OR LBGI OR “risk of hyperglyc#emia” OR HBGI OR “time blocks” OR “quality of life” OR QoL OR well-being)

S9 (depress* OR anxiet* OR stress* OR distress* OR self-management OR self-care OR self-regulations OR self-monitoring OR adherence OR compliance OR cope OR coping OR resilien* OR self-efficacy OR “behavioural control” OR confidence OR self-esteem OR “family functioning” OR “family conflict” OR “family cohesion” OR “family flexibility” OR “family relation*” OR “family communication” OR “family problem solving” OR “family support” OR “family responsibility” OR “parental involvement” OR “family environment” OR “family adaptability” OR “social competence” OR “social skills” OR “social development” OR “social communication”)

S10 S1 AND S2

S11 S3 OR S4 OR S5 OR S6 OR S7

S12 S8 OR S9

S13 S10 AND S11 AND S12

Applied Social Sciences Index and Abstracts (39 results)– ProQuest Platform

Notes:

Abstract search field selected (AB)

The database thesaurus or controlled vocabulary of subject terms was searched for key terms of interest available in the database and then ‘exploded’

S1 AB(“Type 1 Diabetes” OR “insulin dependent diabetes” OR T1DM OR IDDM OR “type 1” OR “type I” OR “juvenile onset diabetes” OR “child onset diabetes”) OR MAINSUBJECT.EXACT.EXPLODE("Insulin dependent diabetes mellitus")

S2 AB(adolescent* OR youth* OR juvenile* or teen* OR “young adult*” OR “young people” OR minor* OR pubescent OR “emerging adult*”) OR MAINSUBJECT.EXACT.EXPLODE("Adolescents") OR MAINSUBJECT.EXACT.EXPLODE("Young adults")

S3 AB(“physical* activ*” OR exercis* OR “moderate intensity” OR “light intensity” OR “vigorous intensity” OR “very vigorous intensity” OR “high intensity” OR workout OR “physical training” OR sport* OR “strength training” OR “strength activit*” OR “resistance training” OR “resistance activit*” OR “aerobic training” OR “aerobic activit*” OR “anaerobic training” OR “anaerobic activit*” OR “flexibility training” OR “flexibility activit*” OR “endurance training” OR “endurance activit*” OR “physical education” OR PE OR walking) OR MAINSUBJECT.EXACT.EXPLODE("Physical activity")

S4 AB(“sedentary behav*” OR sit* OR “screen time” OR sedentary) OR MAINSUBJECT.EXACT.EXPLODE("Sedentary people")

S5 AB(sleep* OR alertness OR wakefulness) OR MAINSUBJECT.EXACT.EXPLODE(“Sleep”)
S6 AB(“24-hour movement behav*” OR “integrated behav*”)

S7 AB(“health behav*” OR “health knowledge” OR “health attitude*” OR “health practice*”) OR MAINSUBJECT.EXACT.EXPLODE("Health behaviour") OR MAINSUBJECT.EXACT.EXPLODE("Health beliefs")

S8 AB(HbA1c OR A1c OR “glyc* h?emoglobin” OR glycoh?emoglobin OR “glyc?emic control” OR “glucose control” OR “mean glucose” OR “mean daily glucose” OR hypoglyc?emia OR hyperglyc?emia OR “time in hypoglyc?emic range” OR “time in level 1 hypoglyc?emic range” OR “time in level 2 hypoglyc?emic range” OR “time below range” OR TBR OR “time in target range” OR “time in range” OR TIR OR “time in hyperglyc?emic range” OR “time in level 1 hyperglyc?emic range” OR “time in level 2 hyperglyc?emic range” OR TAR OR “glucose variability” OR “glyc?emic variability” OR “estimated A1c” OR eA1C OR “glucose management indicator” OR GMI OR “hypoglyc?emic episodes” OR “hyperglyc?emic episodes” OR “area under the curve” OR AUC OR “risk of hypoglyc?emia” OR LBGI OR “risk of hyperglyc?emia” OR HBGI OR “time blocks” OR “quality of life” OR QoL OR well-being) OR MAINSUBJECT.EXACT.EXPLODE("Glycaemic control") OR MAINSUBJECT.EXACT.EXPLODE("Quality of life")

S9 AB(depress* OR anxiet* OR stress* OR distress* OR self-management OR self-care OR self-regulations OR self-monitoring OR adherence OR compliance OR cope OR coping OR resilien* OR self-efficacy OR “behavioural control” OR confidence OR self-esteem OR “family functioning” OR “family conflict” OR “family cohesion” OR “family flexibility” OR “family relation*” OR “family communication” OR “family problem solving” OR “family support” OR “family responsibility” OR “parental involvement” OR “family environment” OR “family adaptability” OR “social competence” OR “social skills” OR “social development” OR “social communication”) OR MAINSUBJECT.EXACT.EXPLODE("Anxiety") OR MAINSUBJECT.EXACT.EXPLODE("Depression") OR MAINSUBJECT.EXACT.EXPLODE("Psychological distress") OR MAINSUBJECT.EXACT.EXPLODE("Stress") OR MAINSUBJECT.EXACT.EXPLODE("Selfcare") OR MAINSUBJECT.EXACT.EXPLODE("Adherence") OR MAINSUBJECT.EXACT.EXPLODE("Family functioning") OR MAINSUBJECT.EXACT.EXPLODE("Family relationships") OR MAINSUBJECT.EXACT.EXPLODE("Coping") OR MAINSUBJECT.EXACT.EXPLODE("Social competence") OR MAINSUBJECT.EXACT.EXPLODE("Social skills") OR MAINSUBJECT.EXACT.EXPLODE("Adherence")

S10 S1 AND S2

S11 S3 OR S4 OR S5 OR S6 OR S7

S12 S8 OR S9

S13 S10 AND S11 AND S12

Sports Medicine & Education Index (185 results) – ProQuest Platform

Notes:

Abstract search field selected (AB)

The database thesaurus or ‘controlled vocabulary of subject terms’ was searched for key terms of interest available in the database. The exploded option was not available.

S1 AB(“Type 1 Diabetes” OR “insulin dependent diabetes” OR T1DM OR IDDM OR “type 1” OR “type I” OR “juvenile onset diabetes” OR “child onset diabetes”) OR MAINSUBJECT.EXACT("Diabetes")

S2 AB(adolescent* OR youth* OR juvenile* or teen* OR “young adult*” OR “young people” OR minor* OR pubescent OR “emerging adult*”) OR MAINSUBJECT.EXACT("Teenagers") OR MAINSUBJECT.EXACT("Young adults")

S3 AB(“physical* activ*” OR exercis* OR “moderate intensity” OR “light intensity” OR “vigorous intensity” OR “very vigorous intensity” OR “high intensity” OR workout OR “physical training” OR sport* OR “strength training” OR “strength activit*” OR “resistance training” OR “resistance activit*” OR “aerobic training” OR “aerobic activit*” OR “anaerobic training” OR “anaerobic activit*” OR “flexibility training” OR “flexibility activit*” OR “endurance training” OR “endurance activit*” OR “physical education” OR PE OR walking) OR MAINSUBJECT.EXACT("Exercise")

S4 AB(“sedentary behave*” OR sit* OR “screen time” OR sedentary) OR MAINSUBJECT.EXACT(“Screen time”)

S5 AB(sleep* OR alertness OR wakefulness) OR MAINSUBJECT.EXACT("Sleep")

S6 AB(“24-hour movement behav*” OR “integrated behav*”)

S7 AB(“health behav*” OR “health knowledge” OR “health attitude*” OR “health practice*”) OR MAINSUBJECT.EXACT("Health behavior")

S8 AB(HbA1c OR A1c OR “glyc* h*emoglobin” OR glycoh?emoglobin OR “glyc?emic control” OR “glucose control” OR “mean glucose” OR “mean daily glucose” OR hypoglyc?emia OR hyperglyc?emia OR “time in hypoglyc?emic range” OR “time in level 1 hypoglyc?emic range” OR “time in level 2 hypoglyc?emic range” OR “time below range” OR TBR OR “time in target range” OR “time in range” OR TIR OR “time in hyperglyc?emic range” OR “time in level 1 hyperglyc?emic range” OR “time in level 2 hyperglyc?emic range” OR TAR OR “glucose variability” OR “glyc?emic variability” OR “estimated A1c” OR eA1C OR “glucose management indicator” OR GMI OR “hypoglyc?emic episodes” OR “hyperglyc?emic episodes” OR “area under the curve” OR AUC OR “risk of hypoglyc?emia” OR LBGI OR “risk of hyperglyc?emia” OR HBGI OR “time blocks” OR “quality of life” OR QoL OR well-being) OR MAINSUBJECT.EXACT("Glucose monitoring") OR MAINSUBJECT.EXACT("Quality of life")

S9 AB(depress* OR anxiet* OR stress* OR distress* OR self-management OR self-care OR self-regulations OR self-monitoring OR adherence OR compliance OR cope OR coping OR resilien* OR self-efficacy OR “behavioural control” OR confidence OR self-esteem OR “family functioning” OR “family conflict” OR “family cohesion” OR “family flexibility” OR “family relation*” OR “family communication” OR “family problem solving” OR “family support” OR “family responsibility” OR “parental involvement” OR “family environment” OR “family adaptability” OR “social competence” OR “social skills” OR “social development” OR “social communication”) OR MAINSUBJECT.EXACT("Self-medication") OR MAINSUBJECT.EXACT("Patient compliance") OR MAINSUBJECT.EXACT("Social skills") OR MAINSUBJECT.EXACT("Anxiety") OR MAINSUBJECT.EXACT("Anxiety disorders") OR MAINSUBJECT.EXACT("Families & family life") OR MAINSUBJECT.EXACT("Mental depression") OR MAINSUBJECT.EXACT("Stress") OR MAINSUBJECT.EXACT("Coping") OR MAINSUBJECT.EXACT("Self esteem")

S10 S1 AND S2

S11 S3 OR S4 OR S5 OR S6 OR S7

S12 S8 OR S9

S13 S10 AND S11 AND S12

Wiley Cochrane Library (641 results)

Notes:

Abstract search fields selected (:ab)

“MeSH” headings (controlled vocabulary) were searched and “exploded” [mh]

#1 (“Type 1 Diabetes” OR “insulin-dependent diabetes” OR T1DM OR IDDM OR “type 1” OR “type I” OR “juvenile onset diabetes” OR “child onset diabetes”):ab OR [mh “Diabetes Mellitus, Type 1”]

#2 (adolescent* OR youth* OR juvenile* or teen* OR young NEXT adult* OR “young people” OR minor* OR pubescent OR emerging NEXT adult*):ab OR [mh Adolescent]

#3 (physical* NEXT activ* OR exercis* OR “moderate intensity” OR “light intensity” OR “vigorous intensity” OR “very vigorous intensity” OR “high intensity” OR workout OR “physical training” OR sport* OR “strength training” OR strength NEXT activit* OR “resistance training” OR resistance NEXT activit* OR “aerobic training” OR aerobic NEXT activit* OR “anaerobic training” OR anaerobic NEXT activit* OR “flexibility training” OR flexibility NEXT activit* OR “endurance training” OR endurance NEXT activit* OR “physical education” OR PE OR walking):ab OR [mh Exercise]

#4 (sedentary NEXT behav* OR sit* OR “screen time” OR sedentary):ab OR [mh “Sedentary Behavior”]

#5 (sleep* OR alertness OR wakefulness):ab OR [mh Sleep]

#6 (24 NEXT hour NEXT movement NEXT behav* OR integrated NEXT behav*):ab

#7 (health NEXT behav* OR “health knowledge” OR “health attitude*” OR health NEXT practice*):ab OR [mh “Health Behavior”] OR [mh “Attitude to Health”]

#8 (HbA1c OR A1c OR glyc* NEXT h?emoglobin OR glycoh?emoglobin OR glyc?emic NEXT control OR “glucose control” OR h?emoglobin NEXT a1c OR “mean glucose” OR “mean daily glucose” OR hypoglyc?emia OR hyperglyc?emia OR time NEXT in NEXT hypoglyc?emic NEXT range OR time NEXT in NEXT level NEXT 1 NEXT hypoglyc?emic NEXT range OR time NEXT in NEXT level NEXT 2 NEXT hypoglyc?emic NEXT range OR “time below range” OR TBR OR “time in target range” OR “time in range” OR TIR OR time NEXT in NEXT hyperglyc?emic NEXT range OR time NEXT in NEXT level NEXT 1 NEXT hyperglyc?emic NEXT range OR time NEXT in NEXT level NEXT 2 NEXT hyperglyc?emic NEXT range OR TAR OR “glucose variability” OR glyc?emic NEXT variability OR “estimated A1c” OR eA1C OR “glucose management indicator” OR GMI OR hypoglyc?emic NEXT episodes OR hyperglyc?emic NEXT episodes OR “area under the curve” OR AUC OR risk NEXT of NEXT hypoglyc?emia OR LBGI OR risk NEXT of NEXT hyperglyc?emia OR HBGI OR “time blocks” OR “quality of life” OR QoL OR “well being”):ab OR [mh “Glycated Hemoglobin A”] OR [mh “Quality of Life”] OR [mh “Glycemic Control”]

#9 (depress* OR anxiet* OR stress* OR distress* OR self-management OR self-care OR self-regulations OR self-monitoring OR adherence OR compliance OR cope OR coping OR resilien* OR self-efficacy OR behavioural control OR confidence OR self-esteem OR “family functioning” OR “family conflict” OR “family cohesion” OR “family flexibility” OR family NEXT relation* OR “family communication” OR “family problem solving” OR “family support” OR “family responsibility” OR “parental involvement” OR “family environment” OR “family adaptability” OR “social competence” OR “social skills” OR “social development” OR “social communication”):ab OR [mh Depression] OR [mh Anxiety] OR [mh “Stress, Psychological”] OR [mh “Psychological Distress”] OR [mh “Treatment Adherence and Compliance”] OR [mh “Self Efficacy”] OR [mh “Adaptation, Psychological”] OR [mh “Family Relations”] OR [mh “Social Skills”]

#10 #1 AND #2

#11 {OR #3-#7}

#12 #8 OR #9

#13 #10 AND #11 AND #12

OpenGrey (35 results)

Notes:

OpenGrey Database is less sophisticated and so a simpler search was conducted searching for only the population of interest, returning few results.

Population Search: ("type 1 diabetes" OR “insulin-dependent diabetes”) AND (adolescent* OR youth* OR “young people” OR "emerging adult")

Appendix E: Study One (Supplementary Materials Table S1), Inter-Rater Reliability Between Reviewers.

Title and Abstract Inter-Rater Reliability			
Reviewer 1	*Reviewer 2*	*Cohen's Kappa*	*Level of Agreement*
M.P.	B.H.	0.60	Moderate
M.P.	E.R.	0.72	Moderate
M.P.	S.M.	0.85	Strong
Full Text Inter-Rater Reliability			
Reviewer 1	*Reviewer 2*	*Cohen's Kappa*	*Level of Agreement*
M.P.	B.H.	0.69	Moderate
M.P.	E.R.	0.62	Moderate
M.P.	S.M.	0.64	Moderate

Appendix F: Study One (Supplementary Materials Table S2),

Characteristics of Quantitative Studies.

Data was collated utilising a Microsoft Excel sheet due to the high volume of studies. Please access using the following link
https://www.mdpi.com/article/10.3390/ijerph20054363/s1

Appendix G: Study One (Supplementary Materials Table S3),

Quality Appraisal.

Data was collated utilising a Microsoft Excel sheet due to the high volume of studies. Please access using the following link
https://www.mdpi.com/article/10.3390/ijerph20054363/s1

Appendix H: Study One (Supplementary Materials Table S4-7), Quantitative Studies.

Table S4: Physical Activity and Primary Outcomes

Construct	**HbA1c**			**QoL**			**CGM Metrics†**			**HbA1c** *n/N (%)*	**QoL** *n/N (%)*	**CGM Metrics†** *n/N (%)*
	F	*UF*	*NS*	*F*	*UF*	*NS*	*F*	*UF*	*NS*			
TPA	7	1	13	3	-	2	1	-	-	7/21*(33%)*	3/5*(60%)*	1/1*(0%)*
MVPA	7	1	12	6	-	1	-	-	1	7/20*(35%)*	6/7*(86%)*	0/1*(0%)*
VPA	3	-	5	-	-	-	-	-	-	2/8*(22%)*	-	-
MPA	2	-	5	1	-	-	-	-	-	2/7*(25%)*	1/1*(100%)*	-
LPA	-	-	4	1	-	-	-	-	-	0/4*(0%)*	1/1(100%)	-
Total	19	2	39	11	-	3	1	-	1	19/60*(32%)*	11/15*(79%)*	0/2*(0%)*

TPA, total physical activity; MVPA, moderate to vigorous activity; VPA, vigorous physical activity; MPA, moderate physical activity; LPA, light physical activity; HbA1c, haemoglobin A1c; QoL, quality of life; n, number of favourable associations, N, total number of associations; F, favourable, UF, unfavourable, NS, not significant

†Mean glucose metric utilised to determine associations

Table S5: Sedentary Behaviour and Primary Outcomes

Construct	**HbA1c**			**QoL**			**CGM Metrics†**			**HbA1c** *n/N (%)*	**QoL** *n/N (%)*	**CGM Metrics†** *n/N (%)*
	F	*UF*	*NS*	*F*	*UF*	*NS*	*F*	*UF*	*NS*			
Total SED	-	2	4	-	1	-	-	-	-	2/6*(33%)*	0/1*(0%)*	-
STC	-	4	3	-	-	-	-	-	-	4/7*(57%)*	-	-
STT	-	3	2	-	-	-	-	-	-	3/5*(60%)*	-	-
STS	3	-	-	-	-	-	-	-	-	0/3*(0%)*	-	-
TST	-	3	1	-	-	1	-	-	-	3/4*(75%)*	0/1*(0%)*	-
Total	3	12	10	-	1	1	-	-	-	12/25*(48%)*	0/2*(0%)*	-

SED, sedentary time; STC, screen time computer; STT, screen time TV; STS, screen time schoolwork; TST, total screen time; HbA1c, haemoglobin A1c; QoL, quality of life; n, number of unfavourable associations, N, total number of associations; F, favourable, UF, unfavourable, NS, no significance

†Mean glucose metric utilised to determine associations

Table S6: Sleep and Primary Outcomes

Construct	**HbA1c**			**QoL**			**CGM Metrics†**			**HbA1c** *n/N (%)*	**QoL** *n/N (%)*	**CGM Metrics†** *n/N (%)*
	F	*UF*	*NS*	*F*	*UF*	*NS*	*F*	*UF*	*NS*			
Duration	3	1	10	-	-	1	-	1	3	3/14*(21%)*	0/1*(0%)*	0/4*(0%)*
Continuity or Efficiency‡	1	-	4	-	-	-	1	-	2	1/5*(20%)*	-	1/3*(33%)*
Timing	-	2	1	-	-	-	-	-	-	0/3*(0%)*	-	-
Satisfaction/Quality	1	-	6	-	-	-	-	-	1	1/7*(14%)*	-	0/1*(0%)*
Alertness/Sleepiness	-	-	3	-	1	-	-	-	1	0/3*(0%)*	0/1*(0%)*	0/1*(0%)*
Total	5	3	24	-	1	1	1	1	7	5/32*(16%)*	0/2*(0%)*	1/9*(11%)*

HbA1c, haemoglobin A1c; QoL, quality of life; F, favourable, UF, unfavourable, NS, no significance; n, number of favourable associations, N, total number of associations

†Mean glucose metric utilised to determine associations

‡Where multiple measures of continuity and efficiency were used, the sleep efficiency construct was utilised to determine associations

Table S7**:** Movement Behaviour and Secondary Outcomes

Movement Behaviour	**Depression**				**Anxiety**				**Self-management†**			
	F	*UF*	*NS*	*n/N (%)*	*F*	*UF*	*NS*	*n/N (%)*	*F*	*UF*	*NS*	*n/N (%)*
PA												
TPA	-	-	-	-	-	1	1	0/2*(0%)*	1	-	-	1/1*(100%)*

MVPA	-	-	1	0/1*(0%)*	-	1	2	0/3*(0%)*	-	1	-	0/1*(0%)*
VPA	-	-	-	-	1	-	1	1/2*(50%)*	-	-	-	-
MPA	-	-	1	0/1*(0%)*	-	-	1	0/1*(0%)*	-	-	-	-
LPA	-	-	-	-	-	-	-	-	-	-	-	-
Total	-	-	2	0/2*(0%)*	1	2	5	2/8*(25%)*	1	1	-	1/ 2 *(50%)*
SB												
TSED	-	-	-	-	-	-	-	-	-	-	-	-
STC	-	-	-	-	-	-	-	-	-	-	-	-
STT	-	-	-	-	-	-	-	-	-	-	-	-
STS	-	-	-	-	-	-	-	-	-	-	-	-
TST	-	-	-	-	-	-	1	0/1*(0%)*	-	-	-	-
Total	-	-	-	-	-	-	1	0/1*(0%)*	-	-	-	-
SLP												
Duration	1	1	1	1/3*(33%)*	-	-	1	0/1*(0%)*	4	1	3	4/8*(50%)*
Continuity or Efficiency‡	1	-	-	1/1*(100%)*	-	-	-	-	-	-	4	0/4*(0%)*
Timing	-	-	-	-	-	-	-	-	-	1	-	0/1*(0%)*
Satisfaction/ Quality	3	-	-	3/3*(100%)*	-	-	-	-	1	1	3	1/5*(20%)*
Alertness/ Sleepiness	-	1	-	0/1*(0%)*	-	-	-	-	-	-	1	0/1*(0%)*
Total	5	2	1	5/8*(75%)*	-	-	1	0/1*(0%)*	5	3	11	5/19*(26%)*

Continued

Movement Behaviour	**Coping**				**Self-efficacy**				**Family Functioning**				**Social Competence**			
	F	*UF*	*NS*	*n/N (%)*	*F*	*UF*	*NS*	*n/N (%)*	*F*	*UF*	*NS*	*n/N (%)*	*F*	*UF*	*NS*	*n/N (%)*
PA																
TPA	1	-	-	1/1*(100%)*	-	-	-	-	-	-	-	-	-	-	-	-
MVPA	-	-	-	-	-	-	1	0/1*(0%)*	-	-	-	-	-	-	1	0/1*(0%)*
VPA	-	-	-	-	-	-	1	0/1*(0%)*	-	-	-	-	-	-	-	-

MPA	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LPA	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	-	-	-	-	-	-	2	0/2 *(0%)*	-	-	-	-	-	-	1	0/1 *(0%)*
SB																
TSED	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
STC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
STT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
STS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TST	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SLP																
Duration	-	-	1	0/1*(0%)*	-	-	-	-	-	-	-	-	-	-	-	-
Continuity or Efficiency‡	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Timing	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Satisfaction/ Quality	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Alertness/ Sleepiness	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	-	-	1	0/1*(0%)*	-	-	-	-	-	-	-	-	-	-	-	-

PA, physical activity; TPA, total physical activity; MVPA, moderate to vigorous physical activity; VPA, vigorous physical activity; MPA, moderate physical activity; LPA, light physical activity; TSED, total sedentary behaviour; STC, screen time computer; STT, screen time television; STS, screen time schoolwork; TST, total screen time; F, favourable, UF, unfavourable, NS, no significance; n, number of favourable associations, N, total number of associations.

†Where multiple measures of self-management were reported (e.g., blood glucose checks and a measure of self-management) the measure of the construct was examined in relation to favourable/unfavourable associations due to it being a more complete measure of self-management.

‡ Where multiple measures of continuity and efficiency were used, the sleep efficiency construct was utilised to determine associations

Appendix I: Study One (Supplementary Materials Table 8), Qualitative Studies.

Table S8: Characteristics of Qualitative Studies

Author (Date), Location	Sample Characteristics *(N†, Age, Diabetes Duration, HbA1‡)*	Data Analysis Method	Movement Behaviour	Theme(s) and Related Outcome(s)	Quotation (s)
Bergner et al., (2018 Physical Activity Guidelines Advisory Committee) *USA, Nashville, Tennessee*	**N:** 25 adolescent-caregiver dyads **Age (T1D Adolescent):** 15.56 ± 1.48 years **Diabetes Duration:** 6.15 ± 4.04 years **HbA1c:** 8.93 ± 1.95 %	Thematic Analysis	Sleep	**Theme:** Barriers to Obtaining Sufficient Sleep **Primary:** Glycaemic Control **Theme:** Diabetes Related Sleep Disruptions **Secondary:** Self-Management	**Barriers to Obtaining Sufficient Sleep (Glycaemic Control):** "Usually [TEEN] sleeps fine, unless his blood sugar's high. Then he's up every couple hours" (Caregiver, p544). "it affects it [SLEEP] a little because like sometimes I have to wake up either to pee maybe because my blood sugar's high or I wake up feeling low and need to get something to eat" (Adolescent, p545). **Diabetes Related Sleep Disruptions (Self-Management):** "You have to wake up more, because you have to check your sugar in the middle of the night if you need to" (Adolescent, p545). "I seem more lazy and it's where I don't want to test and I don't want to get up to eat, and if I do eat I don't test and I forget to take my insulin" (Adolescent, p546). "Generally if I don't get enough sleep… I'm not really on top of anything . . . I'm not my usual self. I don't like do things, I just kinda *sit*." (Adolescent, p546). "the lack of sleep would probably cause [her teen] to not be able to keep track of his blood sugars or test when he needs—it probably causes him to be a little lazy about it" (Caregiver, p546).
Quirk et al., (2014)	**N:** 20 Parents	Thematic Analysis	Physical Activity	**Theme:**	**Parents Battle for Blood Glucose control (Glycaemic control):**

UK, England	**Age (T1D Adolescent):** 10.8 ± 2.2 years **Diabetes Duration:** 4.7 years ± 2.6 years **HbA1c:** Not Stated			Parents Battle for Blood Glucose control **Primary:** Glycaemic control **Secondary:** Coping	"they do say when you exercise then you get better blood sugars, but I don't know, it just makes it more uncontrollable in some ways!" (Caregiver, p5). "makes things easier to control" (Caregiver, p09), "the more sport he did that the less hypos he was having" (Caregiver, p19). **Parents Battle for Blood Glucose control (Coping):** "a way of getting out his anger" (Caregiver, p6).
Rechenberg et al., (2018 Physical Activity Guidelines Advisory Committee) *USA, Connecticut*	**N:** 29 T1D Adolescents **Age (T1D Adolescent):** 13.6 ± 1.9 years **Diabetes Duration:** 5.6 ± 3.7 years **HbA1c:** 8.3 + 1.3%	Thematic Analysis	Sleep	**Theme:** The never-ending cycle of disturbed sleep **Secondary:** Anxiety	**The never-ending cycle of disturbed sleep (Anxiety):** "Because I'm scared that if I fall asleep and don't respond to my receiver" (Adolescent, p550). "I panic a lot because one night my blood sugar dropped in the middle of the night and I ended up like having a seizure" (Adolescent, p550). "My mother sets an alarm for 2:30 in the morning and she comes and checks me so she doesn't want me to have to get up in the middle of the night" (Adolescent, p550).
Ryninks et al., (2015) *UK, England*	**N:** 12 T1D Adolescents **Age (T1D Adolescent):** 14.5 ± 1.5 years **Diabetes Duration: NS** **HbA1c:** 8.3%.	Interpretive Phenomenological Analysis	Physical Activity	**Theme:** Benefits of Exercise **Primary:** Glycaemic Control Quality of Life	**Benefits of Exercise (Glycaemic Control):** "keeps your blood sugar at good rates" (Adolescent, 13y, p4) ''It helps to sort of control. I don't really know why but I felt that um, if I'm doing more exercise um I can normally keep my levels at a more consistent rate" (Adolescent, 15y, p4). "Walking is really good for my blood sugars my mum says. I went on a walking weekend with Guides and my blood sugars were really good all the time I was doing that. So that's good for my blood sugars" (Adolescent, 12y, p4). "Exercise kind of helps lower your sugar level. If it's high then you just go outside for a run and then it goes back to normal again (Adolescent, 15y, p5). **Benefits of Exercise (Quality of Life):** "When you're doing exercise you know you're helping your body as well as yourself" (Adolescent, 15y, p5).

					"I feel better for it but that's probably just 'cause I'm enjoying my sport" (Adolescent, 16y, p5). "It keeps you fit and um as well um if you um eat properly as well, then like I said it keeps you fit and nice and healthy" (Adolescent, 12y, p5).
Wenneick et al., (2009) *Europe, Sweden*	**N:** 11 T1D Adolescents and Parents **Age (T1D Adolescent):** 13 (11-16) years **Diabetes Duration: NS** **HbA1c:** Not Stated	Latent Content Analysis	Physical Activity	**Theme:** Physical activity as pleasure and annoyance **Secondary:** Self-Management	**Physical activity as pleasure and annoyance (Self-Management):** "...Now I am going to start swimming four times a week... I have to do the homework some time before...it is all right but I have to monitor my blood sugar, and I have to take some extra insulin if it is too high, or some dextrose if it is too low. I might have to take dextrose before swimming, to make it a bit higher...and I have to go up and monitor my blood sugar somewhere in the middle of the swimming practice...." (Adolescent, p226).
Wilkie et al., (2017) *UK, Scotland*	**N:** 16 T1D Adolescents **Age (T1D Adolescent):** 11.6 ± 2.5 years **Diabetes Duration:** 3.8 ± 4.3 years **HbA1c:** Not Stated	Thematic Analysis	Physical Activity	**Theme:** Motivators Related to Health **Primary:** Glycaemic Control Quality of Life **Theme:** Family and Friends Participating **Secondary:** Family Functioning	**Motivators Related to Health (Glycaemic Control):** '...when he has really high glucose late evening, we have two options: either extra jag or go for a walk and of course now he says "ok let's go for a walk"... after 15–20 minutes come back and sugar is fine' (Caregiver, p152). **Motivators Related to Health (Quality of Life):** 'happy' or 'amazing' after exercise (Adolescent, p153). **Family and Friends Participating (Family Functioning):** "because it's funner with other people, like you can keep moti-vated, but you can also have a laugh while you're doing it...,' (Adolescent, p153).
Quirk et al., (2016) *UK, England*	**N:** 12 T1D Adolescents	Thematic Analysis	Physical Activity	**Theme:** Children's physical activity is motivated	**Children's physical activity is motivated by perceived positive outcomes, fun and enjoyment (Quality of Life):**

	Age (T1D Adolescent): 10.8 ± 0.9 years **Diabetes Duration:** 4.3 ± 3.1 years **HbA1c:** 55.1mmol/mol (Range = 41mmol/mol - 72mmol/mol).			by perceived positive outcomes, fun and enjoyment **Primary:** Quality of Life **Theme:** Children perceive difficulties that make physical activity harder **Primary:** Glycaemic Control	"I feel quite satisfied" (Adolescent, p03), "cheerful" (Adolescent, p12) "I like walking because it really relaxes me" (Adolescent, p11). **Children perceive difficulties that make physical activity harder (Glycaemic Control):** "Sometimes with football when my bloods go low and stuff ...I have to you know, come off or not go on or don't go on, just need to wait for them to come back up. [H: How does that make you feel?] Annoyed because not so long ago, there was a football match and I was supposed to be coming on at half- time, so I had to delay that as well, so I ended up not playing as long" (Adolescent, p03).
Blake et al., (2018 Physical Activity Guidelines Advisory Committee) *UK, England*	**N:** 11 Parents **Age (T1D Adolescent):** 11.38 ± 2.69 years **Diabetes Duration:** 6 ± 3.3 years **HbA1c:** Not Stated	Thematic Analysis	Physical Activity	**Theme:** Benefits and challenges of PA with T1D **Primary:** Glycaemic Control	**Benefits and challenges of PA with T1D (Glycaemic Control):** "'what we've learned is that physical activity keeps the spikes and the lows more moderate so you don't fluctuate as much... the physical activity just makes that more stable" (Caregiver, p4).

N: sample size; T1D: type 1 diabetes; HbA1c: glycated hemoglobin; PA: physical activity.

Appendix J: Data Collection, Participant Information Sheet and Consent Example (Older Adolescents, ≥16 years)

Participant Information Sheet for Adolescents with Type 1 Diabetes [Quantitative, 16 and above]

[FOR USE WITH STANDARD PRIVACY NOTICE FOR RESEARCH PARTICIPANTS]

Name of department: School of Psychological Sciences and Health
Title of the study: The Balancing Healthy Days Study

Introduction
This study is conducted by Mhairi Patience (PhD student), Dr Xanne Janssen, Dr Megan Crawford and Dr Alison Kirk. The investigators of the current study are all part of the School of Psychological Sciences and Health at the University of Strathclyde, Glasgow. This project is part of a student research project supported by the University of Strathclyde and will form part of a doctoral (PhD) thesis. Contact details of each researcher are available at the end of this form in case you have questions about the research. Please make sure you read all the sections below before deciding to take part.

What is the purpose of this research?

We want to understand how adolescents with type 1 diabetes build and balance 'healthy days' by examining their physical activity, sitting and sleep. We want to see if the ultimate healthy day exists and how this may affect health. We will do this by measuring your full day of activity (day and night) and how this may affect your glucose control and quality of life.

1)

Do you have to take part?

No, you do not have to take part in this study. Not taking part in this study will **not** have any consequences for you. If you do agree, but change your mind once you start the study, that is ok too. You can stop participating in the study at any point.

What will you do in the project?

1. If you decide you would like to take part in the study, you can **give consent** by ticking the box at the bottom of this page.
2. Once you have done this, you will be directed to an **online questionnaire** asking you for a few pieces of contact information, demographic information (for example your age), your most recent HbA1c and measures of diabetes quality of life. This questionnaire takes 5-10 minutes to complete (promise!). There is also a question asking if you would be willing to share your CGM glucose data with us (please note: this is **optional**) and potentially take part in additional research with us later in the year.
3. Then, we will send you a **device to wear on your wrist for two weeks**. This device will record your activity during the day and night. We will also ask you to record information about your sleep (for example when you go to bed and when you get up) during those 2 weeks. At the end of the two weeks, you will be asked to **send back the device** in a pre-paid envelope. If you also selected the option to share your CGM glucose metrics with us, we will also ask you to share your CGM glucose metrics collected during the previous 2-weeks with the researchers. You will do this by accessing your CGM account (e.g., LibreView, Dexcom Clarity etc) downloading your glucose data for the 2-weeks previous and sharing this with us securely. Guidance videos and information will be made available to help you with this.

Activity monitor (ActiGraph GT3x-BT)

Size: 4.6 x 3.3 x 1.5cm

Weight: 19g

This monitor will be worn on a Velcro strap positioned on the non-dominant wrist and records physical activity and sleep. This should be worn throughout the whole 24-hour day.

Who can take part in this research?

We are looking for individuals who:

- Are aged between 11-18 years old.
- Have been diagnosed with type 1 diabetes.
- Are English speaking and can understand the requirements of the study.
- Live in the UK.
- Have no mobility related issues.
- Have not been diagnosed with a sleep disorder.

What are the potential risks to you in taking part?

There are no significant risks associated with participation in this study. If you are upset by anything, then let your parent or someone else you trust know. It is important that you share your feelings with someone who can help support you. There are also websites that you can visit on your own if you don't have anyone you can feel you can speak to. Here are some examples:

- Young Minds is a charity that supports adolescents and their caregivers. They have a lot of information about feelings, coping or mental health.
- Samaritans is a mental health charity providing emotional support to anyone in emotional distress, struggling to cope, or at risk of suicide throughout Great Britain and Ireland, often through their telephone helpline.
- Mind provide advice and support to empower anyone experiencing a mental health problem.

Additionally, the watch and tracker that we are asking you to wear ***might*** get itchy or cause redness (although this is rare). If that happens, take the watch/tracker off and speak to the research team.

Finally, this research team does not have the clinical expertise to monitor the blood glucose readings for indication of diabetes management. If you have concerns about your diabetes you should speak with your consultant. There is also blood glucose information and other diabetes related resources available from diabetes specific websites, for example Diabetes UK.

What information is being collected in the project?

We will collect different types of information:

1. Contact Information: name, home address, email address and phone number so we can communicate with you during the study and send movement behaviour devices to your home.

2. Demographics: age, sex, ethnicity, socioeconomic status, diabetes duration, last measured HbA1c, treatment modality (insulin type, delivery, and frequency) so we can later describe the people involved in the study.

3. Psychosocial outcomes: a quality-of-life measure specific to your diabetes.

4. Movement behaviours: this will tell us how active you are, how much you sleep and how much time you spend sitting.

5. OPTIONAL (CGM Glucose metrics): If you selected 'yes' to being interested in sharing your CGM data with us in the questionnaire, we will ask you to share your CGM glucose data over the 2-weeks you wore the activity devices.

Who will have access to the information?

Only the people that are doing this research will be able to look at the data and use it.

Every participant taking part in this study will be given a unique number linked to your data to ensure they are anonymous. Information that might identify you like your name, email address or home address will be removed from the main dataset and stored separately in a secure password protected location affiliated with the University.

Any information from this study will be presented as part of a PhD thesis/book. Additionally, we will try to publish the results in a journal or present them at conferences. The data from this study will also be made available as "open data" through a research data repository. This means the data that does not identify you will be publicly available and may be used by other researchers. Information such as your name, address or email address will not be included in the dataset we upload.

Any person who wants access to that data will need approval from us. If you do not want your data to be included in this database, please let us know so we can remove your data. You will need to do this before you finish the study.

Confidentiality will only be breached (e.g., we will contact a guardian or respective authority) if the researcher believes you are at risk of serious, imminent harm to yourself or others (e.g., if you endorse suicide ideation – feeling hopeless, plans to end life, completion of acts in anticipation of death))

Where will the information be stored and how long will it be kept for?

After the study is finished, we will keep your contact information (name, email address, home address, phone number) for 3-months to ensure we can contact you if we have any questions about the information provided. Following this 3-month, we will then delete all contact information so all the information we store indefinitely is your study ID and the data gathered. This is to ensure the data cannot be linked back to you. The data will be stored indefinitely on the University of Strathclyde data repository (Pure) as 'open data'. If you decide to withdraw from the study at any point, we will still use the anonymised data (data that cannot identify you personally) that we will have collected from you up until that point. You can request that your personal data is removed from our files.

What happens next?

If you would still like to take part, you can tick the consent boxes at the bottom of the page and then complete the questionnaire. Then a researcher will be in contact with you.

If you do not wish to take part, simply close this webpage. You do not need to give any reason for this. If you do not want to be involved in this activity, we would like to thank you for your attention and taking the time to read this participant information sheet.

If you have any questions or are unsure about anything written here, just contact one of the researchers and we will answer your questions.

All personal data will be processed in accordance with data protection legislation. Please read our Privacy Notice for Research Participants for more information about your rights under the legislation.

Researcher contact details:

Miss Mhairi Patience
PhD Research Student
mhairi.patience@strath.ac.uk

Dr Megan Crawford
Lecturer in Psychology
megan.crawford@strath.ac.uk

Chief Investigator details:

The Chief Investigator for this research is Dr Megan Crawford, a lecturer in Psychology at the University of Strathclyde, Glasgow.

Email Address: megan.crawford@strath.ac.uk

Ethical Approval

This research was granted ethical approval by the University of Strathclyde Ethics Committee

If you have any questions/concerns, during or after the research, or wish to contact an independent person to whom any questions may be directed or further information may be sought from, please contact:

Secretary to the University Ethics Committee
Research & Knowledge Exchange Services
University of Strathclyde
Graham Hills Building
50 George Street
Glasgow
G1 1QE

Telephone: 0141 548 3707
Email: ethics@strath.ac.uk

Consent Form for Adolescents with Type 1 Diabetes

Name of department: School of Psychological Sciences and Health
Title of the study: The Balancing Healthy Days Study

Please Note: The below statement will be available on the Qualtrics questionnaire and participants will be asked to tick the box next to it to confirm they have read the participant information sheet, understand the information given fully and give full consent to participating in the project.

❑ I confirm that I have read and understood the information within the participant information sheet for this study and I consent to being a participant in the project.

Appendix K: Data Collection, Baseline Questionnaire

Note: The QR code on the recruitment infographic can be scanned or the available link can be followed that will direct participants to the questionnaire.

<u>Section 1: Eligibility Screening Questions</u>

2) *Note: To be eligible for this study participants must answer (yes, yes, yes, yes, no, no) then they will be asked a question about their specific age group to determine consent procedure. If they are not eligible, they will be directed to a screen explaining they are not eligible for the study and thanking them for their interest.*

Instructions: Please answer the following information about yourself.

1. Are you between 11-18 years old?

   3) ❑ Yes

   4) ❑ No

   5)

2. Have you been diagnosed with type 1 diabetes?

   6) ❑ Yes

   7) ❑ No

   8)

3. Do you live in the UK?

   9) ❑ Yes

   10) ❑ No

11)

4. Do you speak fluent English?

   12) ❑ Yes

13) ❑ No

14)

5. Do you have any mobility related issues or require walking aids?

15) ❑ Yes

16) ❑ No

17)

6. Have you been diagnosed with a sleep disorder?

18) ❑ Yes

19) ❑ No

20)

Section 2: Questions to determine consent procedure

1. Please specify your age group:

❑ I am 16 years or older

❑ I am aged 11-15 years

Note:

- *16 years or older will proceed to PIS, consent and can complete baseline questionnaire.*
- *Younger than 16 years will proceed to PIS and consent, however, before completing the baseline questionnaire verbal consent will also need to be obtained due to the age range (so we can validate who is completing questionnaire). This will be explained and 'Qualtrics' software will be utilised to confirm a date an online Zoom can take place to obtain consent/assent.*

2. Please enter your email address (Only if 11-15 years):

i. *Open Text*

Note: Once Q2 responses have been recorded a message will read, "Thank you – a researcher will see you on the date you selected for your Zoom session."

Section 3: Baseline Questionnaire

Contact Information

1. Are you:

    21)❑ a caregiver/parent of an adolescent with type 1 diabetes

    22)❑ an adolescent with type 1 diabetes

23)

2. What is your first and last name?

    i. (Open Text)

    24)

3. What is your childs first and last name? (Only if Q1 first option selected)

    25)

4. Please enter an email address we can contact you on?

    i. (Open Text)

    26)

5. What is the first line of your home address?

    i. (Open Text)

    27)

6. What is your postcode?

    i. (Open text)

    28)

    29)

Interest in related study

1. “Would you be interested in participating in additional research conducted by our group in the future?

30)❑ Yes

31)❑ No

32)

Adolescent Demographic Questions (Informed by the Scottish Health Survey)

1. What is your age?

i. (Open Text)

33)

2. What is your sex?

34)❑ Male

35)❑ Female

36)❑ Other (Please specify)

37)

3. What is your ethnic group?

❑ White

❑ Asian

❑ Asian Scottish

❑ Asian British

❑ African

❑ Caribbean or Black

❑ Mixed or multiple ethnic groups

❑ Other ethnic group (Please specify)

4. How many years have you been diagnosed with type 1 diabetes?

i. (Open Text)

5. What was your last measured glycated haemoglobin HbA1c?

    i. (Open Text)

6. What type of insulin do you currently use?

    i. (Open Text)

7. How do you deliver your insulin?

    38)❑ Pump

    39)❑ Pen

8. How many times per day do you administer insulin?

    i. (Open Text)

    40)

9. How do you measure your blood glucose levels?

    ❑ continuous glucose monitor

    41)❑ flash glucose monitor

    42)❑ finger prick

    43)

10. What type of Continuous Glucose Monitor do you use? (Only if Q9 first option selected)

    44)❑ Freestyle Libre (Abbott)

    45)❑ Dexcom (G4, G5, G6)

    46)❑ Guardian and Guardian Link (Medtronic)

    47)❑ Eversense (Senseonics)

    48)❑ Other

1. (Open Text)

49)

11. Would you be willing to share your CGM data for this research? (Only if Q10 first 4 options selected as these are CGM types used with software we are utilising)

50) ❑ Yes

51) ❑ No

Quality of Life Measure

In the past ***7 days****, how much of a* ***problem*** *has this been for you …*

ABOUT MY DIABETES ***(problems with…)***	**Never**	**Almost Never**	**Some-times**	**Often**	**Almost Always**
1. I feel hungry	0	1	2	3	4
2. I feel thirsty	0	1	2	3	4
3. I have to go to the toilet too often	0	1	2	3	4
4. I have stomach aches	0	1	2	3	4
5. I have headaches	0	1	2	3	4
6. I feel like I need to throw up	0	1	2	3	4
7. I go "low"	0	1	2	3	4
8. I go "high"	0	1	2	3	4
9. I feel tired	0	1	2	3	4
10. I get shaky	0	1	2	3	4
11. I get sweaty	0	1	2	3	4
12. I feel dizzy	0	1	2	3	4
13. I feel weak	0	1	2	3	4
14. I have trouble sleeping	0	1	2	3	4
15. I get bad-tempered or grumpy	0	1	2	3	4

In the past ***7 days****, how much of a* ***problem*** *has this been for you …*

TREATMENT - I ***(problems with…)***	**Never**	**Almost Never**	**Some-times**	**Often**	**Almost Always**
1. It hurts to get my finger pricked	0	1	2	3	4
2. It hurts to get insulin injections	0	1	2	3	4
3. I am embarrassed by my diabetes treatment	0	1	2	3	4
4. My parents and I argue about my diabetes care	0	1	2	3	4
5. It is hard for me to do everything I need to do to take care of my diabetes	0	1	2	3	4

Whether you do these things ***on your own or with the help of your parents****, please answer how hard these things were to do in the past* ***7 days****.*

TREATMENT - II ***(problems with…)***	**Never**	**Almost Never**	**Some-times**	**Often**	**Almost Always**
1. It is hard for me to take blood glucose tests	0	1	2	3	4
2. It is hard for me to take insulin injections	0	1	2	3	4
3. It is hard for me to exercise or do sports	0	1	2	3	4
4. It is hard for me to keep track of carbohydrates	0	1	2	3	4
5. It is hard for me to carry a fast-acting carbohydrate around with me	0	1	2	3	4
6. It is hard for me to eat snacks when I go "low"	0	1	2	3	4

In the past ***7 days****, how much of a* ***problem*** *has this been for you …*

WORRY ***(problems with…)***	**Never**	**Almost Never**	**Some-times**	**Often**	**Almost Always**
1. I worry about "going low"	0	1	2	3	4
2. I worry about "going high"	0	1	2	3	4
3. I worry about long-term complications from diabetes	0	1	2	3	4

In the past ***7 days****, how much of a* ***problem*** *has this been for you …*

COMMUNICATION ***(problems with…)***	**Never**	**Almost Never**	**Some-times**	**Often**	**Almost Always**
1. It is hard for me to tell the doctors and nurses how I feel	0	1	2	3	4
2. It is hard for me to ask the doctors and nurses questions	0	1	2	3	4
3. It is hard for me to explain my illness to other people	0	1	2	3	4
4. I am embarrassed about having diabetes	0	1	2	3	4

Note: Once questionnaire is completed message reads, "Thank you for completing our questionnaire. A researcher will be in contact with you soon for the next stages of research."

Appendix L: Data Collection, Follow Up Emails

Note: The yellow highlighted sections were adapted depending on who the email was being sent to.

Subject: The Balancing Healthy Days Study: Research Device Information

Hi <<Name of Participant>,

Thank you for completing the questionnaire! In the next few days, we will send to your home address a study pack that will instruct you on device attachment and wear! The address this study pack will be sent to will be:

[ENTER HOME ADDRESS TO CONFIRM]

This pack should contain:

- 1x accelerometer device (to measure your activity)
- 1x participant information booklet (to tell you how to **1)** attach the device; **2)** how to wear the device; **3)** how to record bedtime, wake time and when you remove device)
- 1x prepaid return envelope (so you can return the device following study completion without any cost)
- 1x contact information if issues arise
- 3x research stickers

Thank you very much for participating and I hope you have a wonderful day.

Best wishes,
Mhairi Patience
PhD Student and Tutor
School of Psychological Sciences and Health
Psychology Group
University of Strathclyde

Contact me: mhairi.patience@strath.ac.uk
Twitter: @mhairi_patience
LinkedIn: Mhairi Patience

Appendix M: Data Collection, Research Packs

Balancing Healthy Days

Study Pack Information

University of Strathclyde Glasgow

University of Strathclyde Humanities & Social Sciences

Study Pack Summary

Hello and thanks for getting involved – we look forward to the research!

This **participant study pack** contains everything you need to know to complete the study and information explaining what to do. However, if you still have any questions please get in touch we will be delighted to hear from you and help out J

This study pack is split into sections:

Section 1: Summary of research and lead researcher contact details

Section 2: Device Wear Log (for you to complete and send back to us).

Section 3: Device Wear Instructions (so you know how to attach the device)

You should also have a few things we also emailed to your home:

- 1 x Actigraphy watch (for you to wear)
- 1 x pre-paid envelope (so you don't have to pay any money sending the device and diaries back to us)

Remember to send this study pack back to us after the two weeks along with your device!

Section 1: Summary of Research and Contact Details

In summary, over the next 2 weeks you will be required to:

1. Wear your **Device** watch
2. Complete your **Device Wear Log** each day

After two weeks, we will be in touch to get you to post everything back to us (the device and this study pack) using the envelope we gave you. This envelope means you do not need to pay to send it back to us J

Lead Researcher contact details:

Mhairi Patience PhD: mhairi.patience@strath.ac.uk

If you have any concerns with how this research has been conducted please get in touch using the following email: ethics@strath.ac.uk

Section 2: Device Wear Log

Date: ____________________________ (when you should start wearing your device)

Participant ID: ____________________________ (don't worry about this too much! It is your study identity, so your information stays safe)

Note: Hey! In addition to the actigraphy watch, we have also given you a device wear log asking you about your bedtime, when you get up and any time you take off the monitor for the 2 weeks you are wearing the device. Do your best to fill it out – it would really help piece together the information from the device. Thanks again!

Day	What time did you get into bed?	What time did you fall asleep?	What time did you wake up?	What time did you get out of bed?	Did you take your monitor off?
Monday					1. What time did you take the device off your wrist: 2. How long did you take it off for: 3. Why did you take it off:
Tuesday					1. What time did you take the device off your wrist: 2. How long did you take it off for: 3. Why did you take it off:
Wednesday					1. What time did you take the device off your wrist: 2. How long did you take it off for: 3. Why did you take it off:

Thursday					1. What time did you take the device off your wrist: 2. How long did you take it off for: 3. Why did you take it off:
Friday					1. What time did you take the device off your wrist: 2. How long did you take it off for: 3. Why did you take it off:
Saturday					1. What time did you take the device off your wrist: 2. How long did you take it off for: 3. Why did you take it off:
Sunday					1. What time did you take the device off your wrist: 2. How long did you take it off for: 3. Why did you take it off:

Section 3: Device Wear Instructions

1. What is an actigraphy watch?

An actigraphy watch is a device that records information about sleep and wake patterns.

2. How long will I need to wear an actigraphy watch for?

You will wear the watch for the full day for 2 weeks (if possible).

Start date: ____________________________

End date: _____________________________

This will help us get a fuller understanding of how activity impact different people's type 1 diabetes.

3. Should I ever take the watch off?

Only take the watch off if:

- you take a shower or bath, swim or wash dishes. The actigraphy is not waterproof and should not be dunked under water

4. How do I wear an actigraphy watch?

You should wear the actigraphy watch securely on the hand you use least, using the Velcro to securely fasten the watch comfortably.

Wear the actigraphy watch so the back of the red box (flat side) is against your wrist, as close to the skin as possible.

5. How do I use an actigraphy watch?

You do not need to do anything other than put the watch on your wrist. The actigraphy watch will automatically start monitoring your activity at **00:00 on the ________________________**.

6. Wear Log

In addition to the actigraphy watch, we have also given you a device wear log that asks you about your bedtime, when you get up and **any time you take off the monitor**. This helps us piece together the information we get from the device.

7. How do I return the actigraphy watch?

On ________________________, after 2 weeks of wearing the actigraphy watch, you can return your completed wear log and actigraphy watch to the University of Strathclyde using the pre-paid return envelope enclosed in your study pack.

8. Important Notes

The activity monitor is water resistant NOT waterproof. Please do not wear the device while bathing, swimming, or other water-based activities, but do remember to put the device back on afterwards.

These monitors are expensive, so please take care of them

If the watch is causing redness or itchiness, remove the actigraphy watch. Please contact us if this happens.

If an orange light comes on and remains on, the actigraphy watch may not be recording properly. Please contact us if this happens

The actigraphy watch battery is limited, so if you cannot start wearing your watch by ________________________, please contact us to reset your actigraphy watch start time.

Appendix N: Data Collection, Follow Up Email for Qualitative Involvement

Hey [NAME],

Hope you are having a lovely week! Just wanted to email to say we have got the device back and have sent you a £10 amazon gift voucher to say thank you very much for taking part in this important research!

We also wondered if you are still interested in the other aspect of the research which involves having another chat with me about what you think about physical activity, sitting and sleep?

I would love to hear about your thoughts and opinions on this and it will help the research further 😊

If you are still interested in having a brief chat with me just reply to this email!

Have a great day,

Mhairi Patience
PhD Student and Tutor
School of Psychological Sciences and Health
Psychology Group
University of Strathclyde

Contact me: mhairi.patience@strath.ac.uk
Twitter: @mhairi_patience
LinkedIn: Mhairi Patience

Times Higher Education University of the Year 2012 & 2019
Times Higher Education Widening Participation Initiative of the Year 2019
The University of Strathclyde is rated a QS 5-star institution

Appendix O: Verbal Consent Meeting (young adolescents, 11-15 years).

Capacity to consent meeting

Full Meeting Script

Hi <participant name>
My name is <name>. I'm one of the researchers working on the project.

1. Consent to record

Before we begin, do you mind if I record this meeting?

This is just a quick meeting to make sure that you understand what the project involves and a chance for you to ask questions you have. We will also confirm your consent to participate in the study

2. Parent/guardian present

Who is this you've got here with you today?

####### if no parent/guardian - ask adolescent to get them
####### if no parent/guardian available – reschedule meeting

From reading the participant information sheet in the survey, what do you think you will be doing in the study?

3. Explain the study

#I'll just run through the key points of the study and if you have any questions just stop me and ask

What the study involves

This goal of this study is to learn more about how young people with type 1 diabetes behave. We want to know how well you **sleep**, how much time you spend being **physically active a**nd how much you **sit** during the day to see how these behaviors affect **glucose control** and **emotions/feelings.**

You don't have to take part, it's up to you and if you don't that's not a problem – you can change your mind at any point.

If you do want to take part, you <adolescents name> will have a discussion lasting about 30-45 minutes about your thoughts around physical activity, sitting and sleep and how this may affect your diabetes. We could even have this discussion today if you decide that you would like to take part or organize a better suited day for you.

Does that all make sense to you? Do you have any questions?

Are there any risks

The study is safe and there is nothing involved that can hurt you.

However, if something does upset you, then speak to your parents or someone else you trust – it's important to talk to someone about how you are feeling.

Do you have any questions?

What information will we collect?

We will just need your name, age and email address but we have most of this from your involvement in the last bit of research you kindly helped us out with.

we will also have audio and video recordings of the online Zoom focus groups so that we can later analyse but don't worry, this will be deleted once we have written everything out.

Is that all okay with you? Any questions?

Data security and information storage

Only the people doing the research will be able to see your data and use it. We give you a unique number and all your data will be linked to that number without showing any information that could identify you personally. A summary of the results will be published, but nothing personally identifiable to you.

We will only break privacy, such as contacting a parent or specialist if the researcher thinks you are at risk of serious, immediate harm to yourself or others

After the study is finished, we will keep your contact information for 3 months in case we have any questions about the information provided. After three months, we will delete all of your contact information, keeping only your unique number and the data gathered.

That's a summary of the study, do you have any questions you would like to ask?

Consent

11-years

Are you happy to participate in the study?
Parent/guardian are you happy for <child name> to participate?

Great. All we need now is to get verbal consent from <childs name> and consent from <childs caregiver>.

Adolescent Consent

For the recording, could you please say “I consent to participate in the study”

Caregiver Consent

For the recording, could you please say “I consent to <child name> to participate in the study”

12-15 years

IF the child understand study?

Are you happy to participate in the study?
Parent/guardian are you happy for <child name> to participate?

Great. All we need now is to get verbal consent from <childs name> and assent from <childs caregiver>.

Adolescent Consent

For the recording, could you please say “I consent to participate in the study”

Caregiver Assent

For the recording, could you please say “I assent to <child name> to participate in the study”

12-15 years

IF the child does NOT understand study?

Are you happy to participate in the study?
Parent/guardian are you have for <child name> to participate?

All we need now is verbal consent from you [the participant] and your parent/guardian.

4. **Adolescent Consent**

For the recording, could you please say “I consent to participating in the study”

5. **Parent consent**

Now, parent/guardian, could you please say “I consent to <participants name> to take part in the study”

4. Next steps

IF they want to interview now

Ok perfect lets get started. For this interview your caregiver will need to leave the room so we can have a chat. Is that alright <NAME> we can call you back through when we are done but should only be 30-45 minutes?

IF they want to interview later

That's everything for just now. Next, we will send <participants name> confirmation of the date we agreed for interview and we shall see you on the day!

If you have any questions at any point during the study, please don't hesitate to contact the research team – Mhairi is running the study and you can find her contact details on the participants information sheet or in an email

If you don't have any questions, we can finish up there

Thank you for your time and I hope you have fun doing our study!

Appendix P: Participant Debrief Information

The impact of 24-hour movement behaviours (physical activity, sedentary behaviour, and sleep) on glucose control and psychosocial outcomes in adolescents with type 1 diabetes.

Thank you for taking part in our studies! Now that it is finished, we would like to just explain briefly why we conducted the research!

We are interested in 24-hour movement behaviours. These are all the behaviours in the full 24-hour day and include physical activity, sedentary behaviour (sitting) and sleep. We are interested in figuring out how all these behaviours influence one another and particularly, how they all jointly affect glucose control and psychosocial outcomes in adolescents with type 1 diabetes.

Previous research has looked at all these behaviours individually but not together as a whole and research suggests the way these behaviours interact has important implications for physical and mental health! The research from this study will contribute to the current research on movement behaviours and their impact on physical and mental health in adolescents with type 1 diabetes.

If you feel affected by issues raised by this research and would like to discuss any concerns, please contact the study supervisor on the details provided below.

If you have any other questions about the research, please do not hesitate to contact any of the researchers. Their details are listed below:

Miss Mhairi Patience

PhD Research Student

mhairi.patience@strath.ac.uk

Dr Megan Crawford

Lecturer in Psychology

megan.crawford@strath.ac.uk

Appendix Q: Study Three, Qualitative (Supplementary Materials 1), Accelerometer Data Processing Information and Rationale

Accelerometer wear site:

- Participants wore accelerometers on their non-dominant wrist.
- Participant wear compliance is enhanced greatly when worn on the wrist, especially within the adolescent population (Duncan et al., 2018; Fairclough et al., 2016).
- Accelerometers worn on the wrist provide a more suitable attachment site for capturing 24-hour movement behaviours throughout the entire day (Rosenburger et al., 2019).

Valid day criteria:

- ≥ 10 hours or ≥ 600 min·d−1 (Fairclough et al., 2023).

Valid week criteria:

- ≥ 3 valid weekdays and ≥1 valid weekend day across the entire two weeks of wear (Fairclough et al., 2023).

Non-wear classification:

- Accelerometer non-wear time is detected on the basis of statistics derived from a rolling time window. A step-in time is classified as non-wear if both of the following criteria are met for at least two out of the three accelerometer axes:
    - The standard deviation of the accelerations is less than accelerometer brand specific reference values, which for most brands is 13.0mg (1mg = 0.00981m.s-2)
    - The range of accelerations (i.e., maximum value minus minimum value) is less than 50mg.
- The size of the rolling time window and the size of the steps it takes in time are defined by argument windowsizes, a vector with length three. More

specifically, the second value (mediumsize window, default = 15 min) and the third value (longsize window, default = 60 min) are used.

Cut-point algorithm:

- Hildebrande (2014) cut points were used based on ENMO (m g per 1s) metrics:
    - SED as < 35.6
    - LPA as ≥ 35.6
    - MPA as ≥ 201.4
    - VPA as ≥ 707

52)

Sleep-wake algorithm:

- Van Hees et al (2015) heuristic algorithm was utilised to estimate sleep duration.

References:

Duncan S, Stewart T, Mackay L, Neville J, Narayanan A, Walker C, et al. Wear-Time Compliance with a dual-accelerometer system for capturing 24-h behavioural profiles in children and adults. Int J Environ Res Pub Health. 2018;15(7):1296.

Fairclough SJ, Noonan R, Rowlands AV, Van Hees V, Knowles Z, Boddy LM. Wear compliance and activity in children wearing wrist- and hip-mounted accelerometers. *Med Sci Sports Exerc.* (2016) 48:245–53. doi: 10.1249/MSS.0000000000000771

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Appendix R: Study Three (Supplementary Materials 2), Adolescent Semi-structured Interview Guide

Welcome and Topic Overview

Hello and welcome to the session. My name is BLANK, I am a PhD student at the University of Strathclyde and I will be having a quick discussion with you today if that is still alright?

We will be talking about specific activities like physical activity, sitting and sleep. These are all the activities you might take part in during the 24-hour day.

Ground Rules
Before we start having a chat, I just want to say that there are no right or wrong answers to the questions I ask, I am interested in hearing everything and anything you have to say.
You can talk about good things and bad things and your honest opinion to the questions I ask you would be great! All your comments will be useful, and I look forward to hearing them.
During our chat, we will be on a first name basis but don't worry we will not use any names in our report. We will also remove any information you mention during the interview that could identify you. You can be assured that no information will be shared outside this discussion to anyone unless I feel like you might need some additional help (for example, if you get really upset chatting about some things you are asked)
I will be audio and video recording these interviews as I don't want to miss any of your useful comments. I would like to be completely present and listen carefully to everything you say, so having audio and video will help me analyse the data later. I would just like to confirm the audio and video recording of this interview is ok with you before we begin?

Opening Question
Well, let's begin. Hopefully you can see my name on the screen as a reminder, but you pronounce my name as 'BLANK'. Please just let me know if you need anything throughout the interview.

Main Questions

Ok, if you are ready to start we can start chatting about the activities you might do in a 24-hour day, remember these include physical activity, sitting and sleep.

Awareness (RQ1)

1. What do you think about each of these activities?

2. Are you aware of any activity recommendations or advice?

a. Is there somewhere specific you get these recommendation/advice?

53)

Interaction (RQ2)

3. Do you believe physical activity, sitting and sleep influence each other within a day? In what way?

Impact (RQ3 and RQ4)

4. How would you describe a day where you had good activity patterns?

   a. How would this affect your mood and glucose control?

5. How would you describe a day where you had bad activity patterns?

   a. How would this affect your mood and glucose control?

6. Who would you say is most affected by your own activity patterns?

   a. Why did you choose this individual?

Evolution (RQ5)

7. How do you believe your activity patterns change as you grow up?

   a. Why do you think this is?

Closing Questions

1. Would you like to add any other information related to our discussion today?
2. Are there any other components that would be of importance to discuss that we have not touched on today?
3. Do you have any comments or questions for me?

Once all comments have been received by participants:
Thank you very much for your participation. If you have any questions, then please do not hesitate to contact me

Appendix S: Study Three (Supplementary Materials 3), Codebook of Themes

Themes (Subthemes)	Subthemes	Definitions	Examples from Transcripts
Theme 1: Sleep and PA understood and valued above SB		Adolescent understands and values sleep and PA more than SB.	“I definitely think about how much physical activity and how much sleep I am getting quite a lot but sitting doesn’t really play into it.” “Isn’t it eight hours of sleep minimum. Half an hour to an hour of physical activity and I’m not sure about sitting.”
Theme 2: Recognition of movement behaviours interconnection		Adolescent perceptions on how sleep, PA and SB might interact and impact one another.	“I feel like if you don’t get a lot of sleep you’re going to be sitting for ages. You’re not going to be kind of physical as well. They all kind of interlink.” “If you haven’t slept a lot then the next day you don’t want to be going out for loads of walks, you don’t want to go out for a run, you don’t

			want to ride a bike you just kind of sit and you just kind of do nothing.”
Theme 3: Movement behaviours interact with health outcomes	*Mood*	Adolescent perceptions on how sleep, PA and SB interacts with their mood.	“‘If I have a day and I have been sitting around all day, I’ve not done any exercise and got no sleep I get really grumpy.” “If I got not a lot of sleep and I was just tired and moody and cranky then I would just be like ‘aw I don’t want to do this’ so I just kind of sit there. I would be like ‘you guys do it – I’m not doing it”.
	Glycaemic Control	Adolescent mixed perceptions on how sleep, PA and SB interacts with their glycaemic control.	“My bloods will probably be like more in range, more in target and then depending on the physical activity maybe like taking a dip or a high.” “A good night sleep isn’t going to change my blood glucose throughout the day I wouldn’t say.”

			"But if I have been sitting down and eat something then they generally do like jump up and then down again." "Definitely a bad sleep will impact my mood and then how my control is because I'm a bit like 'I don't want to deal with that now.'"
	Glycaemic control as a barrier to movement behaviours	Adolescent perceptions of glycaemic control as a barrier to sleep, PA and SB.	"I think the thing with sleep is it doesn't affect my blood sugars so the issue in sleep is if something happened that's made my blood sugar go low whilst I'm asleep." "But yeah, so I probably would be a bit cranky if I was a bit low. If I am low, I literally won't do anything I will just sit there and be like 'I can't get up.'" "Sometimes I will wake up and be like ok it's not worth exercising today because I can see that it's going to be a really bad day with my blood

			sugars anyway, I don't want to throw another factor into it."
Theme 4: Movement behaviours within the environmental context of the adolescent	School	Adolescent perceptions of school and how it affects their sleep, PA and SB participation and understanding.	"On a weekend I know a lot of schools had like a sports day thing. Now it's summer holidays you are either doing more exercise or you are not - like doing less exercise." "Well in school obviously you're going to be like sitting a lot but that's kind of guaranteed." "I usually go to my bed at like half nine or ten now because I'm in a school routine but when I'm not it's kind of all over the place and I'm just like my sleep pattern is just so like all over the place. It kind of gets ruined and I feel icky."
	Caregivers	Adolescent perceptions of their caregivers role in their sleep, PA and SB.	"The only issue with sleep is when I wake up in the middle of the night and if I have a hypo right, I've got a pump so if I have a high – I'm a very deep sleeper so, if I've got a high I just sleep like this *imitates sleeping* and my dad just like comes in and says '[NAME]' and I'm like half-

			awake. So, he just types it into the pump anyway, so it is not an issue.” “If I’m at the gym, I have to text my mum and be like ‘aw my bloods are low, I can’t walk home’ or whatever, she has to come pick me up. Do you know what I mean? It’s constantly, she is constantly with me yeah.”