

**Integrating GPS, accelerometry and online mapping technologies: exploring  
built environment correlates of adolescent mobility and domain-specific  
physical activity**

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## Thesis Abstract

Regular physical activity in youth is associated with many aspects of health and development, yet more than half of New Zealand adolescents struggle to meet physical activity guidelines. The modest results of past physical activity initiatives have fostered a growing consensus that sustainable changes in population physical activity will require built environment change. Despite this, current evidence shows inconsistent and sometimes contradictory associations between the built environment and adolescents' physical activity. Accounting for wider mobility patterns and improving measurement specificity are consistently acknowledged as avenues of progression. Through a series of five sequential studies, this thesis aims to explore how recent technological innovations can enhance our understanding of how the built environment is related to adolescents' physical activity and travel behaviours.

The first two studies (Chapters 3 and 4) developed and piloted a novel interactive online mapping tool (VERITAS) for capturing information about adolescents' mobility and interaction with their environment. Each participant successfully located an average of 18 regularly-visited destinations, as well as travel modes, routes, companions, and perceived neighbourhood spaces. Global Positioning System (GPS) travel records were used to demonstrate the accuracy of routes drawn using the mapping interface. Together, these initial studies revealed the functionality and feasibility of online mapping technology for capturing adolescents' wider mobility and travel behaviours.

The third study (Chapter 5) was conceived by recognising that research on adolescents' transport-related physical activity had focused almost exclusively on the school trip. This study integrated GPS and accelerometry to examine how school travel behaviours were representative of wider mobility patterns. Active school travellers (i.e., walk or cycle) accumulated 12.8 min and 14.4 min more moderate-to-vigorous physical activity (MVPA) on weekdays and weekend days, respectively, and spent less time in vehicles during non-school trips. However, individuals who did not travel actively to school still achieved most of their MVPA in the transport domain, suggesting that destinations beyond school also provide important travel opportunities.

The fourth study (Chapter 6) attempted to elucidate these findings by integrating VERITAS, GPS, and accelerometry to examine the entirety of destinations that adolescents frequent, and how travel to these destinations was related to physical activity. VERITAS-reported destinations varied markedly in terms of visit frequency, suggesting

some destination types were more important than others for providing active travel opportunities. Those who reported using active travel modes for most of their weekly trips walked 1.50 km further per weekday, and 2.25 km further per weekend day, compared to those who reported using passive travel modes.

The final study made pragmatic use of the findings in Chapter 6 by creating an objective and spatially-derived measure of destination accessibility that was relevant to adolescents' active travel. Accessibility scores were based on the distribution of local destinations around the home, accounting for both destination type and distance from the residence. Adolescents with high destination accessibility achieved 13.9 min more transport-related MVPA and 9.90 min less transport-related sedentary time each day compared to those living in areas of low destination accessibility. These individuals also walked 1.10 km further and travelled 18.6 km less in a vehicle each day. However, total daily MVPA and sedentary time displayed weaker trends, suggesting an element of displacement across physical activity domains.

This body of work demonstrates how recent technologies can be integrated and applied in this research field, and reinforces the importance of capturing domain-specific physical activity and wider mobility patterns in built environment studies. This thesis established that active travel is the primary source of physical activity New Zealand adolescents, and that destination accessibility is strongly associated with transport practices. It is hoped the original information contained within this thesis will contribute to the next generation of physical activity studies, and help encourage the development of more compact cities that promote active living and reduced health inequities.

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## **Attestation of authorship**

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

A handwritten signature in blue ink, reading "Tom Stewart", written over a dotted line.

Tom Stewart, February 2017

## Co-authored works

### *Peer-reviewed journal publications:*

Stewart, T., Duncan, S., Chaix, B., Kestens, Y., Schipperijn, J., & Schofield, G. (2015). A novel assessment of adolescent mobility: a pilot study. *International Journal of Behavioral Nutrition and Physical activity*, 12(1), 18. doi:10.1186/s12966-015-0176-6

Stewart, T., Schipperijn, J., Snizek, B., & Duncan, S. (2016). Adolescent school travel: Is online mapping a practical alternative to GPS-assessed travel routes? *Journal of Transport & Health*. doi:10.1016/j.jth.2016.10.001

Stewart, T., Duncan, S., & Schipperijn, J. (2017). Adolescents who engage in active school transport are also more active in other contexts: A space-time investigation. *Health & Place*, 43, 25-32. doi:10.1016/j.healthplace.2016.11.009

### *Papers under review or in submission:*

Stewart, T., Duncan, S., & Schipperijn, J. (in submission). Towards tailored measures of accessibility in youth: important destinations for adolescents' active travel and physical activity.

Stewart, T., Schipperijn, J., & Duncan, S. (in submission). The development of an adolescent-specific destination accessibility index for predicting transport-related physical activity

### *Peer-reviewed conference presentations:*

Stewart, T., Duncan, S., Chaix, B., Kestens, Y., Schipperijn, J., Schofield, G. *A novel assessment of adolescent mobility: A pilot study*. Presented at the International Society for Behaviour, Nutrition and Physical Activity (ISBNPA), San Diego, May 2014.

Stewart, T., Schipperijn, J., Snizek, B., Duncan, S. *The automated extraction of multimodal trips from GPS data: an innovative processing approach to improve travel mode and route assessment*. Presented at The International Congress on Physical Activity and Public Health (ISPAH), Bangkok, November 2016.

Stewart, T., Schipperijn, J., Snizek, B., Duncan, S. *Adolescent school travel: is SoftGIS a practical alternative to GPS-assessed travel routes?* Presented at The International Congress on Physical Activity and Public Health (ISPAH), Bangkok, November 2016.

## Research chapter contributions

Chapters 3-7 of this thesis are either published in peer-reviewed journals, under review, or in preparation for submission. The percentage contribution of each author is presented below.

### Chapter 3: A novel assessment of adolescent mobility: a pilot study

Tom Stewart.....	80%
Scott Duncan.....	10%
Jasper Schipperijn .....	5%
Grant Schofield.....	5%

### Chapter 4: Adolescent school travel: Is online mapping a practical alternative to GPS-assessed travel routes?

Tom Stewart.....	80%
Jasper Schipperijn .....	15%
Scott Duncan .....	5%

### Chapter 5: Adolescents who engage in active school transport are also more active in other contexts: A space-time investigation

Tom Stewart.....	85%
Scott Duncan.....	5%
Jasper Schipperijn .....	10%

### Chapter 6: Towards tailored measures of accessibility in youth: important destinations for adolescents' active travel and physical activity.

Tom Stewart.....	85%
Scott Duncan.....	10%
Jasper Schipperijn .....	5%

### Chapter 7: The development of an adolescent-specific destination accessibility index for predicting transport-related physical activity

Tom Stewart.....	90%
Scott Duncan.....	5%
Jasper Schipperijn .....	5%



Scott Duncan



Jasper Schipperijn



Grant Schofield

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### Background

The increasing prevalence of noncommunicable disease (NCD) has become one of the greatest public health priorities of our time. NCDs are generally of slow progression and long duration; cardiovascular disease, cancer, obesity, and type 2 diabetes are the most prevalent examples. Of the 56 million global deaths in 2012, 38 million were attributable to NCDs.<sup>1</sup> Lack of regular physical activity is identified by the World Health Organization as one of the four key modifiable risk factors for NCD prevention. In 2013, physical inactivity alone cost \$67.5 billion (international dollars) in healthcare expenditure and lost productivity globally.<sup>2</sup> The economic cost of physical inactivity in New Zealand is also considerable; estimated at NZD \$1.3 billion for the 2010 year, nearly 1% of New Zealand's GDP.<sup>3</sup>

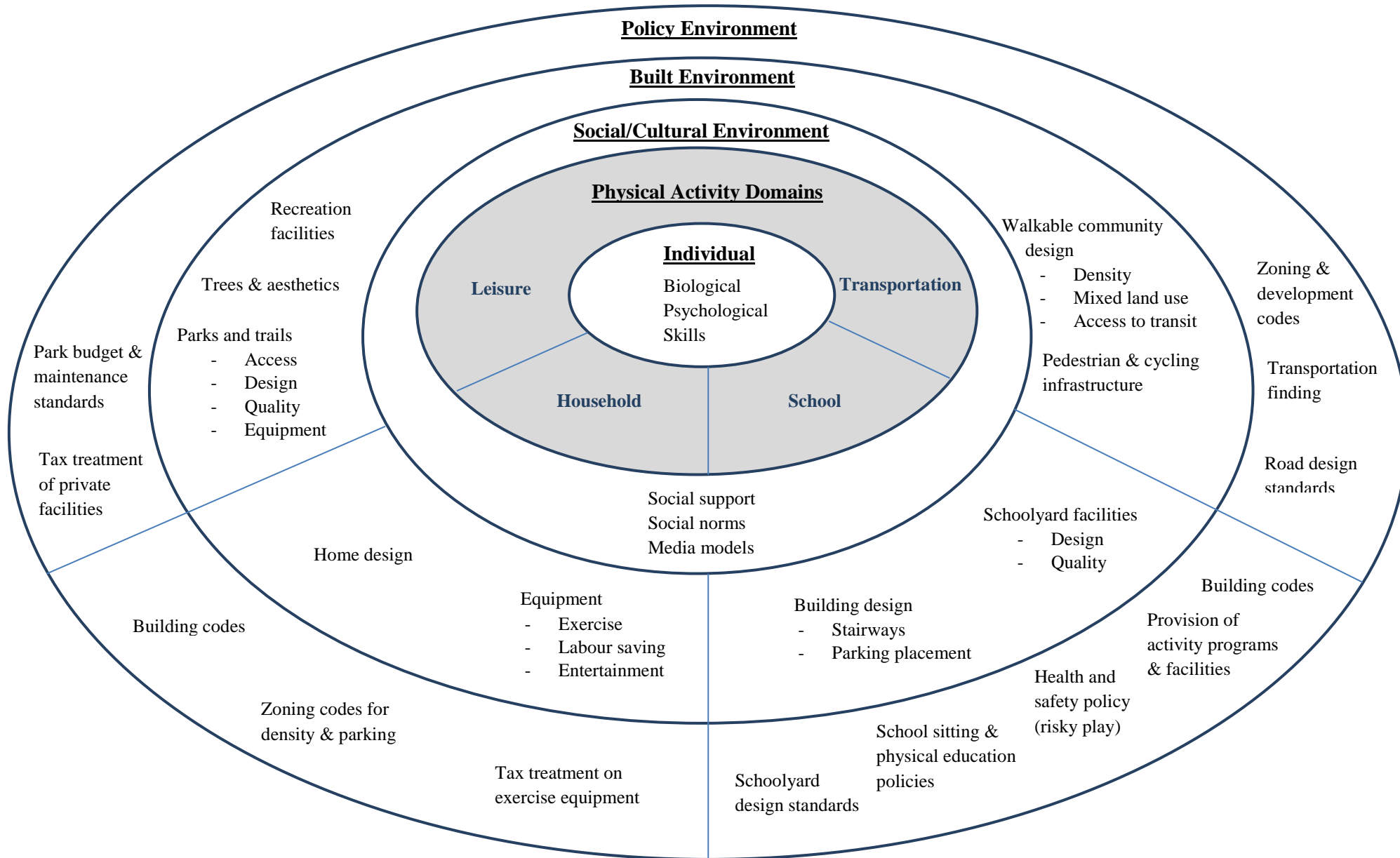
Physical activity is beneficial for many aspects of health and development, particularly cardiovascular fitness, musculoskeletal health, and psychological wellbeing.<sup>4</sup> Developing these behaviours during formative years is essential for fostering positive attitudes and habits that track into adulthood.<sup>5</sup> In fact, physical activity status during adolescence is predictive of health as an adult.<sup>6,7</sup> However, physical activity tends to decline over the course of adolescence by as much as 7% per year.<sup>8,9</sup> As many as 80% of adolescents worldwide fail to achieve the recommended 60 minutes of moderate intensity physical activity each day.<sup>10</sup> In New Zealand, less than half of youth are classified as sufficiently active for health benefit,<sup>11</sup> suggesting the promotion of physical activity during developmental years is of great importance for public health and the wider New Zealand society.

The US Surgeon General's landmark 1996 report suggested that health benefit was not simply a consequence of structured exercise, but activities of everyday living such as walking and playing.<sup>12</sup> This gave rise to the 'active living' paradigm, and caused a global shift from promoting organised, strenuous exercise, to encouraging lifestyle changes where physical activity is accumulated as part of daily life.<sup>13</sup> Walking or cycling for transport—commonly known as active travel—is now considered an ideal strategy for physical activity promotion. Utilising active travel modes have clear individual and collective benefits, including pollution and noise reduction, climate change mitigation,

not to mention the development of navigational skills and the ability to evaluate and manage risk.<sup>14</sup> Despite this, active travel has been in continual decline. In New Zealand in the 1980s, 45% of adolescents travelled actively to school while 21% travelled by car. By the 2000s, active travel modes had dropped to 29% while car travel increased to 37%.<sup>15</sup>

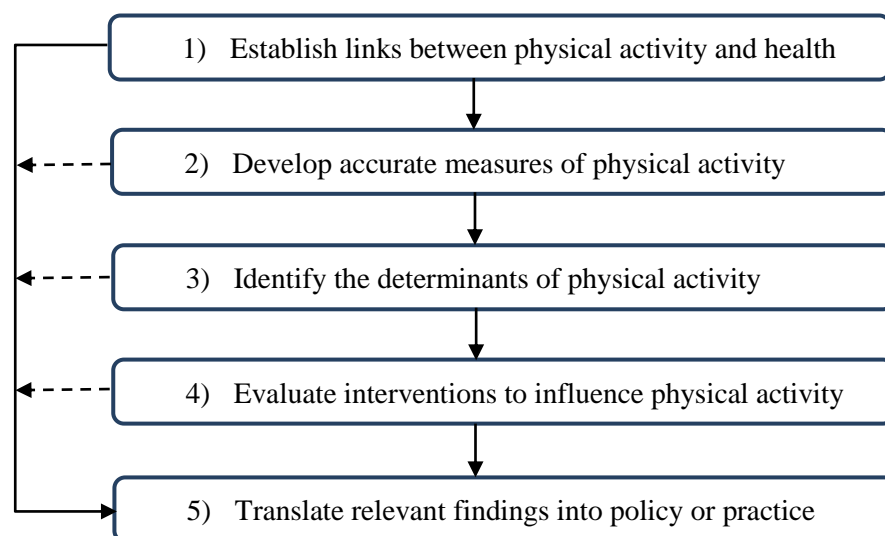
Over the last few decades, significant effort has been invested into identifying evidence-based interventions that are effective in promoting physical activity and active travel. Since the early 2000s, the shortcomings of interventions that target individuals with educational and motivational programs have been recognised,<sup>16</sup> prompting researchers to consider influences on behaviour that are external to the person. The built environment—defined as the totality of places built or designed by humans, ranging from buildings and streets to the layout of communities—is increasingly recognised as an important determinant of physical activity behaviour. Emerging evidence suggests the design and distribution of resources and facilities within an area is related to the amount and type of physical activity that individuals achieve.<sup>17,18</sup>

This is best understood by acknowledging that physical activity is affected by factors operating at several levels, broadly defined as personal (e.g., perceptions and skills), social (e.g., family and cultural norms) and environmental (e.g., built environment and governing policy). These multiple levels of influence are conceptualised through the socioecological model of physical activity behaviour.<sup>19</sup> An important concept within this model is the four domains of physical activity which are used to explain how people spend their time: leisure, transportation, occupation (school), and household.<sup>20</sup> These four domains are affected by different combinations of personal, environmental and policy factors. Figure 1–1 depicts the socioecological model of physical activity that identifies these multiple levels of interaction.



**Figure 1–1.** The socioecological model of the four physical activity domains; adapted from<sup>19</sup>.

A key principle is that motivating individuals to change behaviour (i.e., individual and social determinants) cannot be effective if environments and policies make it difficult or impossible to choose healthy behaviours. Rather, creating environments and policies that make it convenient, attractive, and economical to make healthy choices (and then motivating and educating people about those choices) will be most effective.<sup>19</sup> If designed and implemented correctly, environment and policy intervention can have widespread and sustainable effects on behaviour change, long after initial investment. However, before these can be developed and implemented, it is crucial to identify which environmental factors truly impact on physical activity behaviour, and carefully disentangle how these factors exert their influence. This research process is guided by the behavioural epidemiology framework; a systematic sequence of steps leading to evidence-based intervention and policy change (see Figure 1–2).



**Figure 1–2.** The behavioural epidemiology framework for physical activity; adapted from<sup>21</sup>.

The number of research studies examining how the built environment is related to adolescent physical activity are increasing rapidly (i.e., step three in the framework), yet reviewed evidence shows inconsistencies in hypothesised relationships between the environment and physical activity.<sup>22,23</sup> These inconsistencies hinder the development of robust interventions, and thus evidence-based guidelines for urban planners and policymakers.

## Thesis Rationale

It has been suggested that the equivocal nature of current evidence is caused by a lack of measurement specificity,<sup>24</sup> and conceptual issues that arise from the spatial uncertainty in the actual areas that exert influence on individuals.<sup>25</sup> In built environment studies, it has been common to use *total* physical activity as an outcome measure (i.e., activity from all four domains).<sup>22</sup> These measures may include a substantial amount of physical activity not related to the outcome of interest; for example, total physical activity includes home- and school-based activities, and may attenuate any association between the built environment and transport-related physical activity. Indeed, the distribution of activity across the four domains is not well understood, yet preliminary evidence suggests these patterns are influenced the built environment.<sup>26</sup> There is often a conceptual mismatch between environmental attributes and physical activity domain; for example, associating recreation facilities (i.e., leisure domain) with transport-related outcomes.<sup>24</sup> The socioecological model postulates that each domain of physical activity is affected by different built environment features, but objectively assessing domain-specific physical activity, and isolating environmental variables conceptually related to each domain is notoriously challenging.

The everyday movement of individuals over space between destinations—known as daily mobility—is an important but almost systematically overlooked factor when investigating the relationship between the built environment and physical activity.<sup>27</sup> This is evident when examining transport-related physical activity in youth: current research has focused almost exclusively on travel to and from school, and ignored the role of the built environment on wider mobility patterns.<sup>28,29</sup> It is estimated New Zealand adolescents spend more time per week (collectively) travelling to destinations other than school, such social engagements, shopping, and recreation activities.<sup>15</sup> The types of destinations that adolescents frequent, and if school travel behaviours correspond with wider mobility patterns is not well understood. Examining visited destinations and travel behaviours in their entirety could inform the creation of relevant tools to predict adolescents' active travel behaviours,<sup>30</sup> but practical methods of collecting detailed mobility information are currently absent.

To this end, overcoming several measurement-related issues are consistently acknowledged as avenues of progression.<sup>22,24,31</sup> Recent technological advances have led to a revolutionary ability to capture high-resolution spatiotemporal physical activity

information. The proliferation of consumer grade Global Positioning System (GPS) receivers has allowed researchers to measure where and when physical activity occurs. Innovative data processing techniques may be able to utilise these data to isolate domain-specific physical activity (e.g., physical activity accumulated during transportation). Another emerging method is interactive online mapping surveys, which have recently been proposed as a viable way to capture geographically referenced information about peoples' mobility and interaction with their environment, including locations they visit, how they get there, and their likes and dislikes.<sup>32,33</sup> These tools offer far more detailed information than previous methods, and have the potential to overcome important conceptual and measurement issues. While promising, these techniques are still in their infancy, and their true potential is yet to be realised.

### **Statement of the purpose**

This thesis—nested in the socioecological model of physical activity, and guided by the behavioural epidemiology framework—aims to explore how recent technological and methodological innovations can enhance our understanding of how the built environment is related to adolescents' physical activity and travel behaviours. The proposed research includes developing and piloting novel measurement methods to capture mobility behaviours (an interactive online mapping application) and isolate domain-specific physical activity (through integrating GPS and accelerometry). The primary objectives of this research are:

1. To review existing literature (Chapter 2), with a focus on:
  - ❖ Methods for measuring physical activity and the built environment;
  - ❖ Current evidence on the environmental correlates of adolescents' physical activity, highlighting measurement limitations of previous work.
2. To develop and pilot a novel interactive online mapping technique for capturing adolescent mobility patterns, by:
  - ❖ Conducting a pilot study to assess the feasibility and acceptability of the online mapping tool (Chapter 3);
  - ❖ Assessing the accuracy of travel routes drawn on the online map with actual travel records captured by GPS receiver (Chapter 4).

3. To examine how school travel behaviours are representative of overall mobility patterns (Chapter 5).
4. To explore wider mobility patterns and physical activity, by:
  - ❖ Examining the types of destinations that adolescents frequent, and how travel mode and travel frequency to these destinations is associated with physical activity accumulated in the transport domain (Chapter 6);
  - ❖ Using this empirical travel data to create and test a destination accessibility index tool that is relevant to adolescents' active travel (Chapter 7).

## **Thesis Organisation**

### **Context**

The work presented in this thesis has evolved from a larger research project: The Built Environment and Adolescent New Zealanders (BEANZ) study. This was a three-year project undertaken by AUT's Human Potential Centre, which commenced in 2013. This cross-sectional study was part of an international collaboration across ten countries, governed by IPEN (International Physical Activity and the Environment Network). The BEANZ study aimed to characterise the links between the physical environment and health in New Zealand adolescents. The detailed methodology for the BEANZ study is published elsewhere.<sup>34</sup> Briefly, between February 2013 and September 2014 approximately 800 adolescents were recruited from six secondary schools in Auckland and two secondary schools in Wellington. These are New Zealand's first and third most populated cities, with 1.4 million and 0.5 million people, respectively.<sup>35</sup> A spatial sampling approach was taken to maximise the heterogeneity of built environment exposures, allowing meaningful associations to be detected. Socioeconomic status (SES) and meshblock (New Zealand census tract) walkability indices were calculated for all participants at the selected schools based on their home address. These scores were organised into tertiles, and the highest and lowest tertiles were retained to create four strata: (1) high walkability, high SES; (2) high walkability, low SES; (3) low walkability, high SES and (4) low walkability, low SES. Participants residing in one of these strata were invited to participate in the BEANZ study. The research presented in this thesis was conducted in a subsample of 200 BEANZ participants (approximately 30 per school), who were selected using a stratified approach to balance numbers across the four strata. The sociodemographic characteristics of both samples can be found in Appendix A.

## Thesis structure

This thesis includes distinct publications adapted in chapter format (see Figure 1–3). Chapter 2 establishes the context of the thesis with a brief summary of the literature, focusing on the measurement of physical activity and the built environment, and conceptual issues in previous work. Chapters 3 to 7 are a series of sequential studies that are either published in peer-reviewed journals or under review. Consequently, these are written as stand-alone articles and unavoidable repetition of some information occurs (e.g., participants, methods). Each chapter begins with a preface, which aims to explain the sequential progression of studies, and aid the cohesiveness of the thesis. The general discussion in Chapter 8 provides a summary of key findings in each study, and discusses study limitations, wider implications, and future research directions.

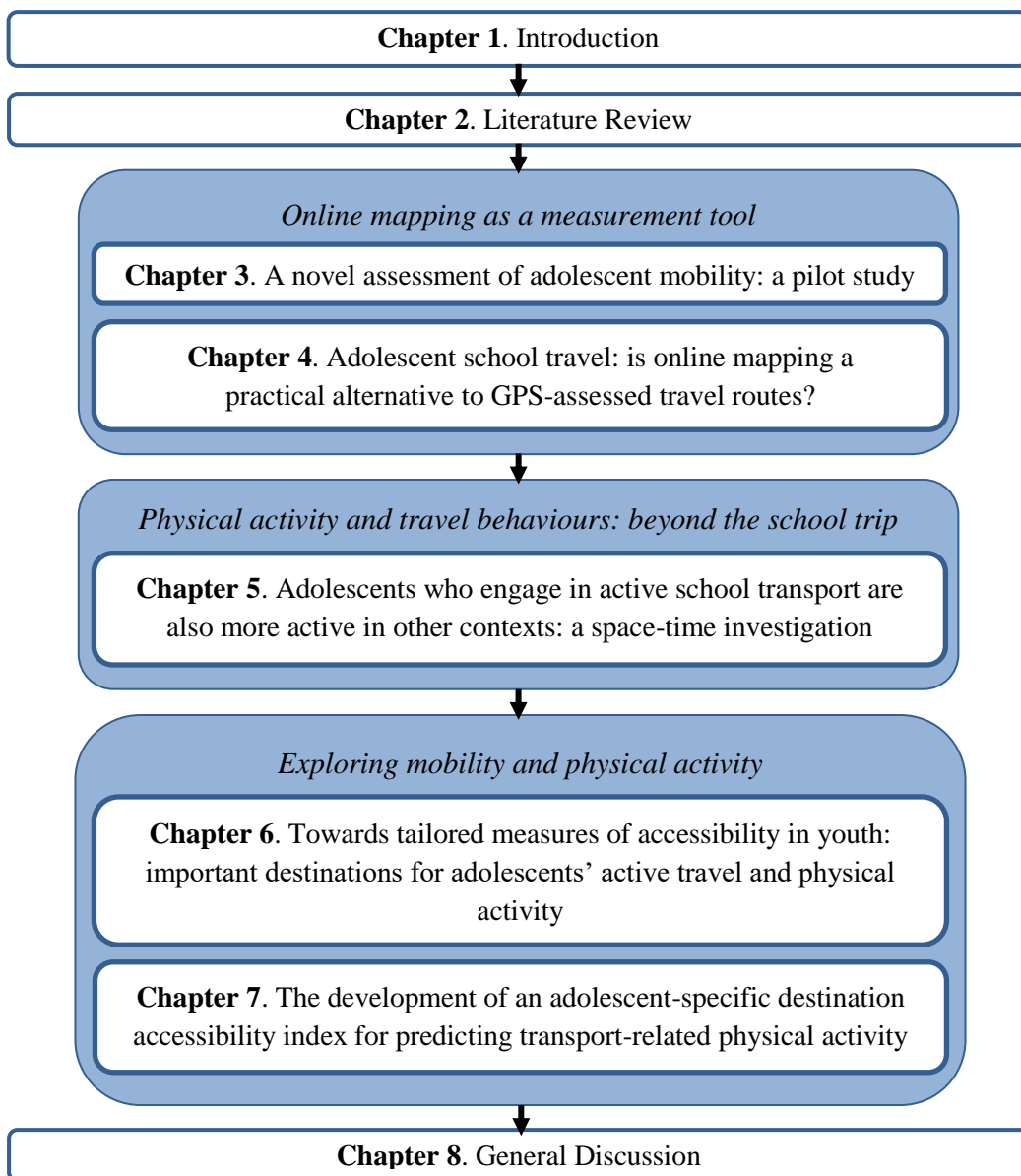


Figure 1–3. Thesis structure and flow.

## **Candidates contributions**

This thesis fulfils the requirements of an Auckland University of Technology Doctoral degree through a significant and unique contribution to this field; refinement of the measurement and characterisation of the built environment as an influence on transport related physical activity. The research questions that form the basis of this work were articulated solely by the candidate. Through this process, the candidate has developed numerous research skills and attitudes necessary to operate in the academic sphere.

Although this body of work was nested within the larger BEANZ study, the candidate played a critical role in the BEANZ research team. The candidate participated in all data collection sessions, and was responsible for the inclusion of GPS receivers in the BEANZ study, which required amendments to the existing BEANZ ethics application. The VERITAS online mapping system was modified and adapted for the BEANZ study by the candidate. The preparation of all physical activity measurement equipment (i.e., accelerometers and GPS receivers), including downloading, storing, and processing the data were the responsibility of the candidate for all eight participating schools.

### **Preface**

Physical activity is important for adolescent health, wellbeing, and the prevention of future chronic disease. Targeting the built environment can have widespread and sustainable effects on physical activity behaviour, but current evidence for adolescents is equivocal. This brief review will establish the thesis context in preparation for the research chapters. The purpose of this review is threefold: (1) to understand the prevalence and health benefits of physical activity in adolescents, and why there has been a research shift towards the environmental determinants of physical activity; (2) to examine the broad scope of measurement techniques employed in physical activity and built environment research; and (3) to summarise the current state of knowledge on the environmental correlates of physical activity in adolescents, highlighting several conceptual issues present in previous work.

## **Background**

### **Physical activity, sedentary behaviour and health**

Physical activity is commonly defined as any bodily movement produced by skeletal muscles that results in energy expenditure.<sup>36</sup> Physical activity can either be structured or incidental; structured physical activity is planned, purposeful, and undertaken to promote health, while incidental physical activity is the result of unstructured daily activities at home, work, or during transport.<sup>37</sup> The importance of physical activity for disease prevention was first established by Scottish epidemiologist Jeremy Morris in the 1950s. Morris showed that drivers of London's double-decker buses were more likely to die from heart disease than bus conductors (who would walk up and down stairs collecting tickets), and that postal office workers had a higher incidence of fatal cardiac infarction compared to postal delivery men.<sup>38</sup> Since then, numerous investigations have confirmed the link between physical activity and various aspects of health and development. This led to the first physical activity recommendations in the United States in 1995,<sup>39</sup> followed by the US Surgeon General's seminal report the subsequent year.<sup>12</sup> This report suggested that physical activity did not have to be planned exercise and that incidental activities like walking and gardening were still beneficial for health, giving rise to the 'active living' paradigm.

Regular physical activity during youth has been associated with cardiovascular health through improved cholesterol and blood lipid profiles,<sup>40,41</sup> musculoskeletal health through improved muscular strength and bone mineral density,<sup>42,43</sup> reduced risk of type 2 diabetes,<sup>44</sup> maintenance of a healthy weight,<sup>4</sup> and reduced symptoms of depression and anxiety, improving psychological wellbeing.<sup>45,46</sup> Emerging evidence from recent epidemiological and physiological research shows that sedentary behaviour—defined as any waking activity of low energy expenditure in a sitting or reclining position—has negative effects on health that are independent of the beneficial effects of physical activity.<sup>47</sup> Periods of prolonged, uninterrupted sitting are suggested to result in abnormal glucose and triglyceride metabolism, and suppressed lipoprotein production,<sup>48</sup> thus increasing the risk of metabolic syndrome, type 2 diabetes, obesity, and cardiovascular disease.<sup>49,50</sup> Notably, these effects may be independent of the consequences which result from a lack of higher intensity physical activity, and hence sedentary behaviour and physical activity are increasingly being viewed as separate constructs and independent

predictors of disease.<sup>51</sup> However, a recent meta-analysis suggests that high levels of physical activity attenuates, but does not eliminate the risk of prolonged sitting.<sup>52</sup>

Physical activity guidelines outline the minimum levels of physical activity required for health benefit. These guidelines are rooted within the four dimensions of physical activity, which describe how bouts of activity are structured: frequency, duration, intensity, and activity type. The current global recommendation for physical activity in young people is 60 minutes of moderate or vigorous intensity physical activity each day.<sup>53</sup> These have been adopted as the national guidelines in many countries, including New Zealand since 2007.<sup>54</sup> Researchers are increasingly interested in where and why physical activity occurs, and the four domains of physical activity are used to describe these patterns: occupational, household, transportation, and leisure. The intensity, duration and frequency of physical activity within each of these domains are used to estimate compliance with physical activity guidelines.<sup>37</sup>

Despite the adoption of formalised guidelines and young people's awareness of physical activity benefits,<sup>11</sup> many fail to achieve the recommended levels of physical activity. It is estimated 80% of adolescents worldwide do not meet physical activity recommendations<sup>10</sup> and New Zealand is no exception; less than half of New Zealand adolescents are classified as sufficiently active for health benefit, many of whom are less active and more sedentary on weekends.<sup>11,55</sup> Longitudinal data show that physical activity declines by 60-70% over the course of adolescence<sup>8,9</sup> while sedentary behaviours increase.<sup>11</sup> In fact, objective data from more than 27,000 youth across 10 countries show that physical activity declines by 4.2% with every year of age.<sup>56</sup> Behaviours developed during developmental years are likely to track into adulthood,<sup>5</sup> so preventing this activity decline is a key strategy for minimizing the incidence of disease in later life.

Lack of regular physical activity is identified by the World Health Organization as one of the four key modifiable risk factors for chronic disease prevention.<sup>1</sup> In 2009, 25% of New Zealand adolescents were overweight and a further 12% were obese<sup>11</sup> and these figures persisted in 2013.<sup>57</sup> This prevalence of overweight and obesity in youth was ranked third in the world by the OECD in 2011.<sup>58</sup> Obesity places individuals at greater risk of developing psychological disorders such as depression<sup>59</sup> and other chronic diseases such as type 2 diabetes.<sup>60</sup> The economic cost of physical inactivity and accompanying diseases is considerable. Physical inactivity was estimated to cost the New Zealand economy NZD \$1.3 billion during the 2010 year.<sup>3</sup> Overweight and obesity alone is estimated to cost

between NZD \$722 million and \$849 million in health care and lost productivity annually.<sup>61</sup> Evidently, developing strategies to promote physical activity in youth is a public health priority.

### **The shift in focus to environmental determinants of physical activity**

Over the last few decades, significant effort has been invested into identifying evidence-based interventions that are effective in promoting physical activity at the population level. Initiatives that target individuals with educational and motivational programs have been common, such as the community-wide ‘Push Play’ and ‘Mission-on’ media campaigns in New Zealand. Although these strategies increase message recognition, they generally do not lead to sustainable changes in behaviour.<sup>16,62,63</sup> One reason for their modest results is that physical activity behaviours are affected by factors external to the person. Ecological models of health behaviour define these multiple levels of influence as personal, social, environmental, and policy factors.<sup>19,64</sup> Behavioural interventions alone may be unable to cause sustained and meaningful levels of behaviour change across a large portion of the population; an individual cannot be expected to change behaviour in an environment that is not conducive to that change. This realisation stimulated the exploration of the environmental determinants of physical activity.<sup>65,66</sup>

The built environment includes all features designed and built by humans, including homes, greenspaces, the transportation system, and the general layout of communities. The built environment provides the context within which individual behaviours occur. Manipulating the environment to increase physical activity (such as the provision of cycling infrastructure or greenspace) is a promising public health approach because environmental features are often ubiquitous, stable exposures that can be modified through urban design and transportation policy. Their influence on local populations could have wide reaching and sustainable effects long after initial investment.<sup>67</sup> New Zealand is known as a highly urbanised country with approximately 85% of the population living in urban areas.<sup>68</sup> However, like many of the world’s cities, New Zealand’s urban regions underwent immense changes during the latter half of the 20th century that were not particularly favourable for promoting physical activity in everyday life.

At the heart of this change is urban sprawl; a post-World War II phenomenon in which people move away from central urban areas into low-density residential communities on

the city fringes. New Zealand's town planning in the 1940s focused on low-density suburbs to and from which people travelled by vehicle. Cities became shaped around suburban rather than purely urban forms, replicating the sprawl of cities in Australia and the United States.<sup>69</sup> Suburbs first developed around public transport routes, but with the uptake of the private automobile, urban sprawl increased further.<sup>70</sup> This coincided with the baby boomer generation where the stereotypical family ideal was the 'quarter acre section' in the suburbs.<sup>69</sup> Through state housing and low-interest home loans, the New Zealand government provided financial incentive for young couples to marry and establish homes and families in the newly expanding residential areas.<sup>71</sup> Sprawl caused the distance between home, workplaces, schools and other important amenities to increase significantly. Motorway systems and roads were built to connect these destinations, promoting car dependency and reducing physical activity opportunities, particularly walking and cycling for transportation.

To date, most evidence on the built environment and physical activity exists for adults, as indicated by numerous reviews.<sup>72-78</sup> These reviews suggest that access to recreation opportunities and other amenities close to home is related to adult's physical activity and health behaviours. However, it is increasingly clear that neighbourhood features have differential effects on physical activity at different life stages, and it is important to identify these associations for all population groups. A neighbourhood may be more salient for individuals who rely more on their local neighbourhood amenities and infrastructure for their daily living. As such, adolescents have been identified as a subgroup that may be more susceptible to their local environment for healthy living opportunities.<sup>79</sup> Despite this recognition, little is known about how the environment affects physical activity behaviours in adolescent groups. As discussed later in this review, current evidence is largely inconsistent, and measurement issues may explain some of these discrepancies. Measurement techniques have progressed rapidly in recent years, and several measurement concepts must be understood prior to the interpretation of descriptive studies.

## **Measurement**

Accurate assessment of physical activity is important for identifying at risk groups, adherence to physical activity guidelines, dose-response relationships, and evaluation of behaviour change initiatives. Quantifying free-living physical activity can be an

extremely difficult undertaking. Unlike other health behaviours, physical activity lacks a precise biological marker, and cardiorespiratory fitness is only a moderate correlate at best.<sup>80,81</sup> Quantifying the environmental determinants of physical activity is even more complex, as it requires the accurate measurement of (1) free-living physical activity, (2) the locations where physical activity takes place, combined with (3) the appropriate assessment of the environment at these locations. Each of these three components can be measured subjectively (i.e., subject responses) or objectively (i.e., using an external tool). Both types are important because physical activity behaviours likely depend on the true nature of the environment as well as how a person perceives their environment. This section summarises the measurement instruments that are currently employed to measure physical activity and aspects of the built environment thought to affect physical activity behaviour.

### **Measurement of physical activity**

The four dimensions of physical activity (frequency, duration, intensity, and activity type) as well as the four domains (occupational, household, transportation, and leisure) are important, but sometimes overlooked concepts when measuring physical activity in built environment studies. An ideal measurement tool would accurately capture each of the four dimensions, as well as the domain in which physical activity occurs, but there is currently no ‘gold standard’ for measuring all aspects of activity behaviour. Past approaches to promote physical activity focused on leisure time and assessment instruments were developed and validated accordingly;<sup>37</sup> however, physical activity can occur in any domain, so any measure of total physical activity should consider all four domains. This is particularly important in built environment studies as different domains of physical activity may be affected by different built environment features.<sup>19</sup>

Measuring physical activity is closely related to energy expenditure. The intensity of a performed activity is directly linked to the rate of energy that is expended. The units commonly used to quantify energy expenditure are kilocalories or the metabolic equivalent (MET). One MET represents the energy expenditure during periods of rest.<sup>37</sup> METs are commonly used to group activities into intensity categories; those between 3–6 METs are referred to as moderate intensity (e.g., brisk walking, gardening) while activities greater than six times resting energy expenditure (6 METs) are considered vigorous (e.g., running, competitive sports). A common method to compute free-living

physical activity is to assess how much time a person spends in different intensity categories on a given day or over a given week. This is important to determine adherence to physical activity guidelines (i.e., 60 minutes of moderate or vigorous activity each day).

### ***Self-reported physical activity***

Self-reported estimates of physical activity are the most common, and early physical activity studies relied almost exclusively on these measures.<sup>82</sup> These methods require participants to either record or recall their activity over a given timeframe. The two main types of self-report are questionnaires and activity diaries or logs. The detail in questionnaires range from a few items that give a global overview of activity, such as the 2-item Exercise Vital Sign,<sup>83</sup> to short recall surveys such as the International Physical Activity Questionnaire,<sup>84</sup> to more comprehensive lifetime recall questionnaires.<sup>85</sup> Diaries are often used to obtain detailed physical activity records in real time, and are therefore less susceptible to recall errors. A well-used example is the Bouchard Physical Activity Record where users record their physical activity every 15 minutes over a three-day period. Each activity is rated in intensity from 1–9 which yields a total energy expenditure score.<sup>86</sup>

Activity diaries are generally burdensome for participants which may result in low compliance and missing data in youth populations.<sup>81</sup> Self-report validation studies have shown strong correlations with measures of vigorous-intensity physical activity, but they are generally less accurate for activities of light and moderate intensity.<sup>87,88</sup> This is because people tend to recall only structured or purposeful exercise and ignore the incidental physical activity that is accumulated throughout the day. The advantage of these techniques is they are easy and cheap to administer, particularly in studies with large samples and restrictive budgets. However, given that the reliability and validity of these data are dependent on reporting precision, the accuracy of these techniques may be compromised.<sup>89</sup>

### ***Pedometers***

Pedometers are hip-mounted motion sensors that record movement during regular gait cycles. These offer a low-cost objective measure of physical activity volume that is quantified as the number of steps taken over a specified interval. Pedometers detect steps

using a horizontal spring-suspended lever arm which moves up and down with vertical accelerations of the hip.<sup>90</sup> Due to the placement and design of the lever arm, pedometers appear to yield more accurate results for running and brisk walking; behaviours that require forward vertical motion. They are unable to adequately capture physical activity involving horizontal motion at the hip.<sup>91</sup> Despite providing a suitable measure of gross physical activity in youth, pedometers cannot measure physical activity duration, and are unable to determine the magnitude of movement. Thus, they cannot differentiate between walking and running, or estimate time spent in different physical activity intensities.

### ***Accelerometry***

Accelerometers are a widely used objective measure of free-living physical activity. Their widespread use is attributed to their ability to measure the frequency, intensity, and duration of physical activity, thereby providing reliable estimates of time spent in different intensities. Since the early 2000s, advances in microelectromechanical technology has significantly reduced the cost of accelerometers and many can now record and store high-resolution data for several weeks. Accelerometers remove the possibility of response bias, are small, robust, and unobtrusive in nature, making them a popular choice for use in youth populations.<sup>80</sup> The basic function of an accelerometer is to measure acceleration in one, two, or three orthogonal planes (anteroposterior, mediolateral, and vertical).

The data output from accelerometers is a recording of body acceleration and deceleration. This is often referred to as raw accelerometer data, and is typically recorded in units of acceleration due to gravity (g). These raw data are usually summed over a user-specified sampling interval known as an epoch, and are then converted into an activity ‘count’.<sup>37</sup> Activity counts are derived units that are largely dependent on individual accelerometers; different brands and models have different on-board systems that process raw data slightly differently, meaning they are often not directly comparable.<sup>92</sup> As such, different accelerometers are calibrated to translate raw or count-based data into meaningful physical activity summaries. These calibration studies are usually performed for individual population subgroups (e.g., children, pre-schoolers or adults) and produce prediction equations or count thresholds that delineate intensity categories (e.g., less than 100 counts per minute is sedentary).<sup>93-95</sup> However, accelerometers are normally worn at

the at the hip, and activities where the hip is largely stationary, such as cycling, may be underestimated.<sup>96</sup>

### ***The Global Positioning System***

The use of Global Position System (GPS) receivers in physical activity research is not to measure physical activity per se, but the locations where physical activity takes place. GPS receivers estimate their position using signals from an array of orbiting satellites. The time difference between signals being sent and received is used to calculate longitude, latitude and altitude to estimate the device's current location on earth. Both spatial and temporal information is stored, providing a chronological sequence of all places visited. Recent improvements in the portability of GPS receivers have made them a convenient option for objectively monitoring movement in outdoor free-living populations.<sup>97</sup> The potential of GPS receivers is realised when combined with accelerometry; detailed contextual information can be obtained, such as locations where higher intensity physical activity occurs, the use of recreation areas, or how much physical activity is accumulated during transportation. Using GPS technology in physical activity research is progressing rapidly, and promises to provide novel insights on how individuals interact with their environment. Despite this, there remain significant conceptual, technical, analytical, and ethical challenges stemming from the complex data these tools generate.<sup>98</sup>

Large-scale GPS studies are currently hindered by technological barriers such as battery life and data storage constraints.<sup>99</sup> Most commercial GPS receivers need to be recharged daily, which increases participant burden and possibly affects compliance. Signal degradation occurs whenever the GPS receiver does not have a direct line of sight to the sky, meaning GPS tends to work poorly indoors.<sup>97</sup> Signal quality may also be heavily degraded in close proximity to buildings and other structures, causing spurious data to be recorded.<sup>100</sup> These factors have major implications for data quality, and extensive data processing time and expertise are usually required to rectify these data prior to analysis. However, initiatives such as the Personal Activity Location Measurement System (PALMS)<sup>101</sup> along with other automated data processing protocols<sup>26,102,103</sup> are making the use of GPS receivers more practical. To date, only one pilot study has used GPS receivers to assess physical activity patterns in New Zealand adolescents.<sup>104</sup>

## **Measurement of the built environment**

The built environment can shape opportunities for physical activity, but it can be challenging to measure properties of the environment that are related to different types of physical activity behaviour. Leisure time activity may be most affected by access to, and characteristics of, recreation areas and facilities.<sup>105</sup> Physical activity in the transport domain may be most related to the proximity and directness of routes to destinations, as well as pedestrian infrastructure, including sidewalks and bicycle lanes.<sup>106</sup> Current measurement techniques can be organised into three categories: (1) self-report questionnaires or interviews, (2) systematic observations or environmental audits, and (3) the use of Geographic Information System (GIS) software.

### ***Self-reported environmental measures***

Evidence gathered on environmental characteristics related to physical activity behaviour are mostly derived from individuals' self-reported perceptions; at least 13 different questionnaires exist for youth alone.<sup>107</sup> Data are collected through interviews or self-administration. The most commonly assessed variables are related to school travel patterns, local land use and amenities, safety from traffic and crime, aesthetic qualities, and pedestrian infrastructure. A frequently used tool is the Neighbourhood Environment Walkability Scale (NEWS) questionnaire<sup>108</sup> and the version adapted for youth populations NEWS-Y.<sup>109</sup>

These types of measures are consistently used as they are cost effective in large scale studies, and perceptions of context are usually strongly related to actual behaviour.<sup>110</sup> However, there is often a large discrepancy between self-report data and contextual data from objective measures.<sup>111,112</sup> The reliability and validity of questions tend to be higher when they refer to concrete attributes, such as existence of parks or sidewalks, and less so for abstract ideas such as safety and crime.<sup>113</sup> Individual perceptions are derived from filtering objective characteristics through past experiences, aspirations, adaptation processes, and individual personality characteristics.<sup>114</sup> This means that two people in the same environment may perceive it differently. One response to this discrepancy has been to reduce the reliance on self-reported data, yet perceptions of context can be a vital counterpart to externally-derived measures; people's perceptions may motivate their behaviour more than the true nature of the environment.<sup>67</sup>

### ***Environmental audits***

An alternative to self-report is the use of systematic observations to objectively quantify built environment attributes. Researchers will usually walk through an area, coding characteristics using a standardised form. Environmental audit tools usually contain close-ended questions, check boxes, or Likert scales. The variables collected are similar to those in self-report questionnaires, such as the presence of retail, traffic calming devices, pedestrian infrastructure, and street furniture.<sup>31</sup> Popular audit tools include the Physical Activity Resource Assessment (PARA),<sup>115</sup> the Systematic Pedestrian and Cycling Environmental Scan (SPACES),<sup>116</sup> and more recently the Microscale Audit of Pedestrian Streetscapes (MAPS).<sup>117</sup> Although direct observation may allow the capture of ‘human qualities’ such as how a place looks and feels,<sup>31</sup> the objectivity of such measures are questionable; these qualities are still open to the subjective perceptions of the auditor, and people may experience these qualities differently. Auditing is time-consuming and expensive for larger areas,<sup>97</sup> and although Google Street View has been proposed as an alternate to in-person assessment, the age and quality of Street View imagery can be problematic.

### ***Geographic Information System***

A Geographic Information System (GIS) is a software package capable of assembling, manipulating, analysing and displaying geographical information.<sup>118</sup> GIS measures are derived from existing spatial data sources which are usually obtained from government agencies or companies. In physical activity research, GIS has been used to construct measures of the density and accessibility of resources,<sup>106</sup> compute routes between destinations,<sup>119</sup> and create buffer zones used to aggregate environmental data.<sup>31</sup> Combined with measures of individual physical activity, GIS has been used to test for associations between a number of built environment features and physical activity behaviours.<sup>118</sup> However, computing accurate geographic information depends on a wide variety of factors, including the completeness of data sources, the area and shape of data aggregation (e.g., how one’s ‘neighbourhood’ is defined), or the metric (e.g., count, density, intensity or proximity) that is used.<sup>120</sup> The choice of these parameters may generate different results, hindering the interpretation and comparability of study findings. Currently, large variation exists in how these environmental variables are conceptualised and computed.<sup>118</sup>

## **The built environment and adolescent physical activity: a summary of evidence**

Studies examining the environmental associations of physical activity have predominantly focused on adults, and to a lesser extent children. The associations between the built environment and adolescent (12–18 years old) physical activity are less understood, as reflected by fewer published studies. Previous findings are summarised and synthesised into four categories of environmental attributes: (1) recreational infrastructure, (2) transportation infrastructure, (3) neighbourhood urban form, and (4) local conditions. Findings for each of these categories are presented below, followed by a discussion of several limitations and conceptual issues that have been identified in previous work.

### **Recreational infrastructure**

The availability or proximity of recreation facilities (such as playgrounds, parks, walking trails and gyms) is one of the most investigated environmental characteristics in youth.<sup>22</sup> These destinations are theoretically related to leisure time physical activity, but may also encourage physical activity in the transport domain through active travel. Access to these destinations is either self-reported or calculated in GIS software. Researchers have used a range of GIS metrics, including the distance, proportion, density or count of facilities within an area.

The presence of recreation facilities have been calculated within 800 m,<sup>121</sup> 1 km,<sup>122</sup> and 1.6 km<sup>123</sup> of home, 1.2 km of school,<sup>124</sup> and in postal code regions.<sup>125</sup> The number and presence of recreations facilities has been positively associated with reported walking trips,<sup>122</sup> reported total physical activity in girls,<sup>124</sup> and total accelerometer-derived physical activity.<sup>123</sup> Adolescent's perceived access to recreation opportunities has also been positively related to self-reported physical activity,<sup>125-127</sup> total accelerometer-derived physical activity<sup>128</sup> and increased odds of reporting walking and cycling trips.<sup>129</sup> The sole study to make use of GPS receivers suggested girls odds of engaging in MVPA was higher in places with parks.<sup>130</sup>

On the contrary, the presence of playgrounds close to home has shown no association with out-of-school MVPA in adolescents,<sup>121</sup> and the distance to the nearest greenspace was unrelated to self-reported leisure time physical activity.<sup>131</sup> Similarly, perceived

access to parks was not related to self-reported or objectively-assessed total physical activity.<sup>132</sup> Despite these contradictory findings, a review concluded that access to recreational facilities was among the most consistent correlates of adolescent physical activity.<sup>22</sup>

### **Transportation infrastructure**

Transportation infrastructure provides the physical connections between destinations, and therefore plays an important role in travel mode decisions. Most research on transportation and physical activity in youth has focused on school travel behaviours,<sup>28,29</sup> but some studies have examined leisure time travel habits. Studies have generally focused on the provision and condition of amenities, such as footpaths and bicycle lanes, or road and traffic hazards.

Travelling actively to school has been linked with the presence of sidewalks (calculated in government-defined traffic analysis zones),<sup>133</sup> perceptions of greater safety from traffic,<sup>134</sup> and pedestrian infrastructure and traffic control measures.<sup>135</sup> Objectively assessed traffic calming devices (e.g., traffic signals and speed bumps) were associated with objectively assessed MVPA after school in adolescent boys.<sup>136</sup> However, the perceived and observed presence of walking and cycling infrastructure has shown no association with self-reported physical activity,<sup>127</sup> objectively measured light intensity physical activity,<sup>137</sup> or walking and cycling to school.<sup>133</sup> Similarly, the number of cycling lanes within an individual's zip code area was not associated with self-reported walking and cycling during leisure time.<sup>129</sup> These inconsistent findings are highlighted by Carver *et al.*<sup>138</sup> who found that perceived ease of cycling was associated with lower (rather than higher) rates of cycling among boys.

### **Neighbourhood urban form**

The physical patterns, layouts, and structures that make up urban centres are collectively called urban form. Urban form has direct implications for pedestrian accessibility, defined the ability to access relevant opportunities or activities on foot.<sup>106</sup> Access-related characteristics of urban form include land use layout, density, and street design. These are hypothesised to influence physical activity by increasing the physical proximity of destinations, thus increasing the likelihood of active transportation.<sup>139</sup>

### ***Land use mix***

Using a mix of land uses (e.g., residential, commercial, institutional, or park and open space) within a localised area reduces the distance to destinations. Land use mix can be derived from questionnaires (e.g., reporting how many destinations are accessible from home), or objectively in GIS using parcel-level data and entropy models to assess the variation of land uses within an area.<sup>18</sup> The distance from residential to non-residential destinations, and intensity measures (count or proportions) have also been used.<sup>31</sup>

In adolescent samples, land use mix has been calculated in postcode areas,<sup>140</sup> 800 m,<sup>141</sup> 1 km,<sup>142,143</sup> and 1.6 km<sup>123</sup> areas around the home. Higher land use mix is associated with increased total accelerometer-derived MVPA,<sup>144</sup> reported number of walking trips<sup>142</sup> and engaging in active transport to school.<sup>140</sup> Land use mix has been linked with walking for youth aged 12–20 but not those aged 5–12,<sup>122</sup> suggesting a variety of destinations is important for older children, and likely reflects their growing independence. A review confirmed that land-use mix was among the most consistent correlates of adolescent physical activity,<sup>22</sup> and alludes to the importance of destination accessibility and diversity for youth physical activity.

### ***Density***

Population or residential density refers to the number of individuals or households in a particular area, and is associated with increased physical activity because destinations can be closer together as the number of people needed to support shops, services, and schools are found in a smaller area. Density is one of the most commonly used GIS-derived variables because data are readily available (census data) and it is easy to compute.<sup>31</sup> Density measures can also be reported via questionnaire through type of residence questions (e.g., single detached housing, multilevel apartment).<sup>109</sup>

Density has been objectively calculated within 500 m,<sup>32</sup> 800 m,<sup>145</sup> and 1.6 km<sup>123</sup> of home, 800 m around school<sup>146</sup> and in government defined zones.<sup>125,133</sup> Density has been positively associated with walking to school in some studies,<sup>140,146</sup> but not others.<sup>32,133</sup> Total accelerometer-derived physical activity was also unrelated to density in several studies.<sup>123,145</sup>

### ***Connectivity***

Street connectivity is the interconnectedness of the street network. A higher connectivity is typically associated with a gridded street design with limited cul-de-sacs. These factors can enhance accessibility by reducing the distance to destinations, and increasing the number of destinations within a specified distance. This has been calculated in a number of ways; intersection count, the number of 3-way or 4-way intersections in an area, or the number of intersections per length of street network.<sup>31</sup>

Like other urban form variables, street connectivity has been calculated within a range of areas, including 800 m,<sup>146</sup> 1 km,<sup>122,147</sup> 1.2 km,<sup>148</sup> and 1.6 km<sup>123</sup> from the residential address. Objectively assessed street connectivity has been positively associated with reported walking trips during leisure time and active travel to school.<sup>122,146</sup> Carlson *et al.*<sup>147</sup> integrated GPS receivers and accelerometers to show that street connectivity was positively associated with time spent walking and bicycling, and negatively related to vehicle time. Conversely, street connectivity has been inversely associated with total accelerometer-derived physical activity in girls,<sup>123</sup> and not related to self-reported school travel mode.<sup>148</sup> Interestingly, residing on a cul-de-sac (which are typically found in areas with low connectivity) was associated with increased MVPA in adolescent boys,<sup>136</sup> possibly due to reduced traffic volume creating opportunities for play.

### ***Composite measures***

Composite indices have been created to capture the combined effect of many built environment characteristics. The trade-off is the complexity of results, which may reduce the interpretability and usability of findings. These indices are usually derived from combinations of the above variables; the most common being the walkability index—a tool consisting of four urban form measures: street connectivity, residential density, land-use mix, and retail floor area ratio.<sup>149</sup> Walkability scores can also be derived from self-report questions (e.g., the NEWS-Y questionnaire). These measures have generally shown consistent associations with physical activity and travel behaviours among adults,<sup>150,151</sup> but children and adolescents tend to show more mixed results.

Walkability index scores have been positively associated with objectively assessed minutes of MVPA in American<sup>144</sup> and Belgian adolescents,<sup>30</sup> but only for those living in deprived areas. A recent GPS study demonstrated walkability indices were positively

related to walking and cycling and negatively related to vehicle time.<sup>147</sup> However, perceived neighbourhood walkability has been inversely associated with self-reported physical activity,<sup>152</sup> and not related to travel mode to and from school.<sup>30</sup> It has been suggested that walkability indices developed based on adult data may be less relevant for younger populations.<sup>30</sup> A child-specific 'playability' index has been developed<sup>153</sup> and more recently a Neighbourhood Destination Accessibility Index for Children (NDAI-C) has been proposed.<sup>154</sup> Currently, no such methods have been developed for adolescent populations.

### **Local conditions**

Recreational, transportation and urban infrastructures exist within the context of local community conditions. These conditions include both positive and negative environmental attributes such as general neighbourhood safety, quality of amenities, and crime rates. Data for local conditions are sometimes sparse and are often collected by the researchers themselves.<sup>31</sup> A few studies have found a negative association between perceived neighbourhood safety and physical activity<sup>138,155,156</sup> but the majority have not.<sup>127,132,157-160</sup> Significant negative associations have also been observed between crime,<sup>156,161</sup> area deprivation,<sup>162</sup> neighbourhood graffiti<sup>155</sup> and adolescent's physical activity, but not in all studies.<sup>163,164</sup> A recent GPS-based study found objectively assessed crime rates were positively (as opposed to negatively) associated with adolescent MVPA.<sup>165</sup>

A possible explanation for these findings is that adolescent's physical activity may be moderated by parent's perceptions of neighbourhood safety. Parents' perceptions of traffic and crime safety have been related to adolescents' active transportation and physical activity.<sup>166,167</sup> Parents' perceived neighbourhood risk has been associated with constrained physical activity behaviours after school,<sup>168</sup> and this translated into lower physical activity and active travel for children and adolescent girls, but not adolescent boys.<sup>168</sup> This is possibly because boys tend to exhibit independent mobility behaviours at an earlier age than girls.<sup>169</sup>

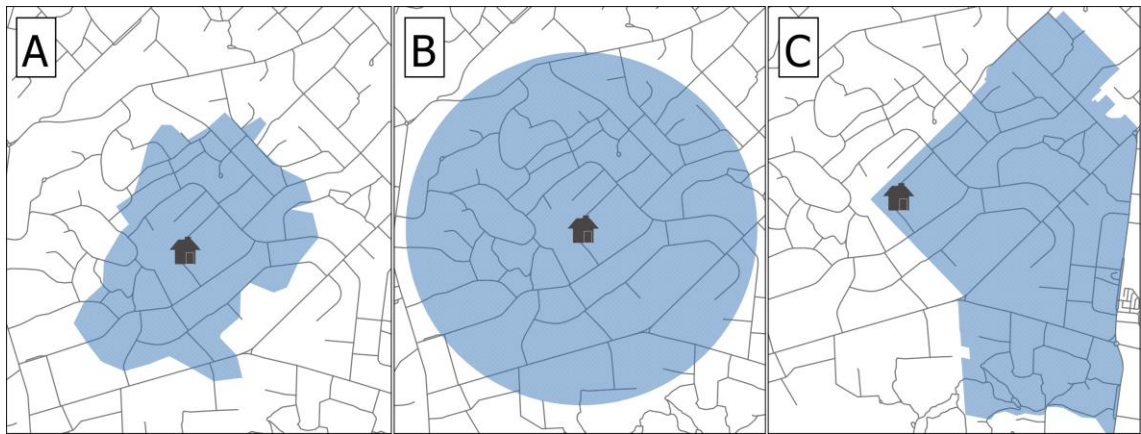
## **Conceptual issues in built environment studies**

There are several conceptual issues in previous work that arise from the spatial uncertainty in the actual areas that exert influence on individuals. Environmental variables need to be calculated within a certain area, but these area decisions tend to lack strong theoretical grounding. Coupled with a general lack of measurement specificity, these issues pose significant methodological and inferential challenges for built environment studies, and possibly explain the contradictory findings of previous work. These issues have been organised into three categories and are described below.

### **1. Defining the ‘neighbourhood’**

One of the weakest theoretical areas in health and environment research is the conceptualisation of place.<sup>170,171</sup> When creating measures of the built environment, data need to be aggregated in an area that is theorised to influence physical activity decisions. However, the defined area of an individual’s environment for physical activity is unknown. Researchers have frequently used the participant’s ‘neighbourhood’ as the spatial aggregation unit; however, conceptualising and measuring neighbourhood-level factors are a major challenge as there is tremendous variation in how ‘neighbourhoods’ are defined and what they represent (see Figure 2–1).

It has been common to use fixed administrative areas (e.g., census tracts or postal code zones) as a neighbourhood unit,<sup>31</sup> yet administrative boundaries are usually developed by government agencies for purposes other than health research. Consequently, these areas may not represent the spaces and facilities that a person uses for their daily activities. To create individualised boundaries (sometimes referred to as ego-centred boundaries<sup>172</sup>), researchers have used GIS software to create buffers around a central point of interest, usually a person’s home. A variety of circular, elliptical, and road network buffers of varying distances have been used.<sup>173</sup> One kilometre buffers are a common, but have ranged from 400 meters<sup>137</sup> to 8 kilometres<sup>174</sup> in adolescent studies. There is no consensus as to which buffer size and type is best, but the spatial definition chosen can severely impact results.



**Figure 2–1.** Variation in area captured by common neighbourhood delimitations.

Panel A represents an 800-m street network buffer; Panel B an 800-m circular buffer; Panel C is a meshblock (smallest census tract unit in New Zealand).

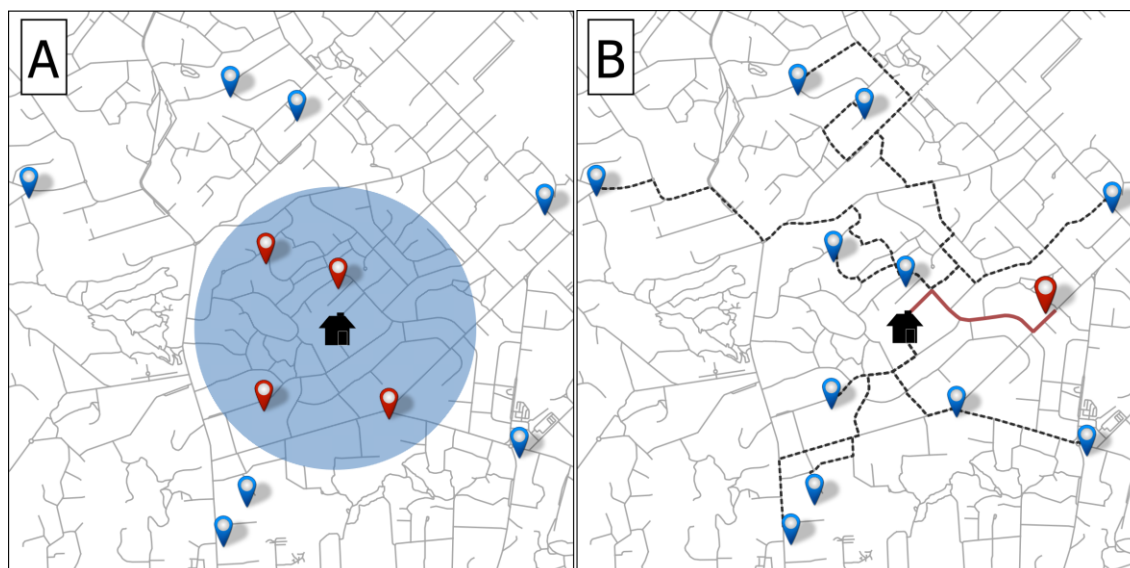
Jago *et al.*<sup>175</sup> found that several environmental variables were associated with adolescent physical activity when using a 400-meter buffer around the home, but these associations did not persist when a 1 mile buffer was used. Similarly, Mitra and Buliung<sup>176</sup> assessed the environmental associations of school travel behaviours in six different neighbourhood delimitations, and found inconsistent results. This suggests that results are sensitive to the scale and zoning of geographic data. In geography, this is known as the modifiable areal unit problem; observed associations differ depending on the scale, zoning and aggregation of geographic units.<sup>177</sup> A buffer distance too small will exclude potentially relevant destinations, whereas a buffer distance too large runs the risk of capturing destinations that are unlikely to play a meaningful role in activity decisions. Buffer choice also has inferential implications; smaller buffer sizes may be unreliable as variables are aggregated using a smaller sample, while larger buffers may reduce sample variance, masking meaningful differences obvious at smaller scales.<sup>176</sup> Interestingly, Broberg and Sarjala<sup>32</sup> found that environmental attributes calculated along school route buffers were stronger predictors of travel mode to school compared to features calculated in the neighbourhood environment.

It has been suggested the selection of spatial units should have strong behavioural justification.<sup>178</sup> However, investigators commonly take a ‘one spatial definition fits all’ approach to defining study subjects’ neighbourhoods, whereby a single neighbourhood definition is applied to all participants regardless of age, gender, location and mobility patterns. One strategy is to use feedback from participants to create individualised definitions of experienced space. A small number of studies have asked respondents to draw their own neighbourhood boundaries on printed paper maps<sup>179,180</sup> which are usually

scanned and imported into GIS software. More recently, interactive online mapping techniques have been proposed to enhance the geographic accuracy of data, ease of collection, and show great promise for collecting perceived neighbourhood spaces.<sup>33,181</sup>

## **2. Accounting for mobility**

A further exposure-related conceptual issue is the almost exclusive focus on the residential neighbourhood in physical activity studies. The everyday movement of individuals over space between destinations—known as daily mobility—has been identified as an important but almost systematically overlooked factor when investigating the relationship between the built environment and physical activity.<sup>27</sup> The environment contiguous to an individual's home is undoubtedly important, but the residential neighbourhood is not the sole mechanism that links place to health.<sup>25</sup> As children progress through adolescence, their social and physical bonds to places near their home are diminished due to increased independence and mobility, and the formation of relationships further from home.<sup>182</sup> Therefore, adolescents may not be confined to these residential boundaries, and may visit an array of destinations beyond the perimeter of their neighbourhoods—a concept known in social science as spatial polygamy.<sup>183</sup> By ignoring travel beyond the neighbourhood, many studies have succumb to the 'local trap'.<sup>184</sup> Similarly, when examining travel behaviours, researchers have tended to focus on school travel, and largely ignored wider mobility behaviours that encompass travel to other destinations (see Figure 2–2).<sup>28,29</sup> However, collecting accurate mobility information is challenging, as these behaviours are highly individualised, complex spatial routines.<sup>185</sup>



**Figure 2–2.** Overlooking mobility in physical activity research.

Markers represent possible destinations where adolescents travel; Panel A demonstrates the residential neighbourhood (blue buffer) may only capture a small portion of visited destinations; Panel B demonstrates the exclusive focus on the school trip (red polyline) and disregard of wider mobility patterns (dashed lines).

### *Measuring mobility patterns*

An ‘activity space’ is a social science construct defined as the areas within which people move or travel during the course of their daily activities.<sup>186</sup> These are expressions of space that encompass an individual’s home, the destinations where they spend their time, and the travel routes between these places. These measures are thought to be more comprehensive summaries of mobility and experienced space compared with traditional neighbourhood measures.<sup>25</sup> There is increasing consensus that environment and health studies should adopt an activity space approach,<sup>25,27,187</sup> yet deriving individual activity spaces requires precursor information about an individual’s travel behaviours within their local context.

Early evidence for mobility patterns was collected using retrospective mobility surveys,<sup>188</sup> and later real-time travel diaries<sup>189</sup> where participants were asked to keep detailed accounts of all trips made. However, detailed information requires a high level of participant engagement and accuracy, which increases participant burden and can lead to incomplete and incorrect information.<sup>190</sup> With technological advances, additional opportunities to assess mobility exist. One approach is to use GPS tracking to capture movement and travel patterns. These GPS records can then be used to create personal activity spaces in GIS using various techniques (e.g., standard deviational ellipses, convex hulls, or daily path area).<sup>191</sup> However, these methods are usually limited to short

measurement timeframes (e.g., one week) and may not reflect true mobility patterns over an extended period.

An alternative is the use of interactive online mapping surveys to gather data on meaningful destinations over an extended period. Online mapping methods have recently gained traction in built environment research as they allow individuals to locate frequently visited destinations anywhere within (and beyond) their neighbourhood, and travel routes between these locations.<sup>33,192</sup> When integrated with survey questions, information can be collected on additional, potentially mediating variables, such as travel frequency, mode of travel, travel companions, and environmental perceptions. This has created new possibilities for exploring an individual's movement through the environment from their perspective. However, these developments generate new needs for operationalising and linking this detailed information with physical activity data.

### **3. The specificity of behavioural outcomes and environmental predictors**

A significant problem for many past studies is a lack of measures that accurately represent the hypothesised relationships between physical activity and the environment. This is often exhibited through a mismatch between the specificity of a research question and the measured outcomes; neither the environment nor the behaviour is quantified appropriately.<sup>193</sup> Although physical activity and built environment research has begun to focus on specific behaviours (e.g., walking for transport) many existing studies use very general outcome measures, and in some cases, environmental predictor variables that are not conceptually related to the behaviour of interest. For example, neighbourhood walkability is theoretically and conceptually related to physical activity via walking for transport, but it has been common to test neighbourhood walkability scores with context-free activity measures such as total physical activity.<sup>23</sup> These measures disregard how and where physical activity is achieved and may not be sensitive to specific environmental attributes. In fact, these 'global' measures may dilute any association between physical activity and the built environment. Researchers have been encouraged to use specific measures of physical activity and behaviour-specific environmental variables to enhance the predictive capacity of their studies.<sup>194</sup>

A review of 103 research papers showed built environment correlates of children and adolescents' physical activity were generally inconsistent.<sup>22</sup> However, they did note the most consistent associations used self-reported domain-specific physical activity (i.e.,

transport/leisure activity), rather than accelerometer-derived physical activity. This suggests that reported physical activity allowed investigators to match environmental attributes with activity domain, something that is not possible with accelerometer data alone. Similarly, perceptions of the neighbourhood have been significantly associated with self-reported walking in the neighbourhood, but not total walking.<sup>195</sup> Although this study used an adult sample, it demonstrates the potential benefit of collecting context-specific behavioural information. The complexity of objectively assessing context-specific physical activity has been the biggest deterrent to answering more specific research questions. By combining GPS, GIS, accelerometry and purpose-built data processing algorithms, it is becoming more feasible to classify activity behaviours into domains or contexts.<sup>26,103</sup> These technologies can substantially increase the accuracy, sensitivity, and objectivity of measures in physical activity and built environment research.

## **Conclusion**

The current body of evidence suggests the built environment is related to adolescent physical activity; however, it is not sufficiently advanced to support causal inference or clearly identify environmental characteristics most strongly associated with activity behaviour. Previous findings display inconsistent associations across many built environment variables. There has tended to be a reliance on self-report and more advanced measurement methodologies are in a developmental stage. There is a clear need to incorporate and test strategies to examine wider mobility patterns and domain-specific physical activity. These types of data may provide a solution to several conceptual issues, and present a major step towards more realistic models of the interaction between people and their environments.

### Preface

A review of existing literature revealed that new techniques are needed to understand adolescent mobility patterns, and examine ways to better capture the local neighbourhood environment. This chapter is the first of two studies that examines the feasibility of online mapping techniques for capturing adolescent mobility information. This pilot study details the creation of an online mapping technique designed specifically for adolescents in a New Zealand context. This paper demonstrates the different types of data that are obtainable, and how these data can be used to derive mobility information. The novelty of perceived neighbourhood boundaries is also highlighted, and how these neighbourhood delimitations differ in size and shape from more traditional measures. This study was undertaken during the early stages of this PhD, with the intention of informing subsequent work. Consequently, the sample used in this pilot consisted of 28 participants from the first school. The full paper from this chapter is currently published in the February 2015 issue of the *International Journal of Behavioural Nutrition and Physical Activity* (Appendix D).

## Abstract

**Background:** Daily mobility and travel to non-residential destinations have been identified as important but almost systematically overlooked factors in built environment and physical activity research. The recent development of VERITAS—a web-based application nested within a computer-assisted personal interview—allows researchers to assess daily mobility, travel to regular destinations, and perceived neighbourhood spaces using interactive mapping technology. The aims of this pilot study were (1) to demonstrate the feasibility and functionality of VERITAS in an adolescent sample, and (2) to compare urban form and geometric features of the perceived neighbourhood with traditional neighbourhood delimitations.

**Methods:** Data were collected and analysed for 28 adolescents (14 male). Participants underwent anthropometric assessment before completing the VERITAS survey. Regularly visited destinations, transportation modes, travel companions, and perceived neighbourhood boundaries were captured. The distance between home and each destination was calculated in GIS software. Urban form variables and geometric features were compared between the perceived neighbourhood and 1 mile Euclidean buffers, 1 km network buffers, and meshblocks.

**Results:** In total, 529 destinations were located, 58% of which were outside the perceived neighbourhood boundary. Each participant located between 8 and 29 destinations on the map (mean =  $17.9 \pm 5.11$ ). Destinations varied in terms of visit frequency, travel mode and travel companions. Active travel was inversely associated with distance to destinations ( $r = -0.43$ ,  $p < 0.05$ ) and traveling with adults ( $r = -0.68$ ,  $p < 0.01$ ). Urban form variables and the size and shape of the perceived neighbourhood were different from other neighbourhood delimitations.

**Conclusions:** This study demonstrates the feasibility of using an online mapping interface to assess mobility in adolescents. These results also illustrate the potential novelty of user-defined spaces, and highlight the limitations of relying on restricted definitions of place (i.e., administrative and residential neighbourhoods) in built environment studies.

## Introduction

Physical inactivity is a key contributor to the widespread prevalence of non-communicable disease.<sup>196</sup> Behavioural and motivational approaches to increase physical activity have had relatively limited effectiveness,<sup>197</sup> causing researchers to consider how environmental and policy factors may affect behaviour and health.<sup>198</sup> An accurate assessment of environmental features is paramount for the clarification of these relationships and the development of supportive policy. Although the residential neighbourhood is important when investigating interactions with the environment, current methods of neighbourhood delimitation are equivocal,<sup>199</sup> and the residential neighbourhood is not the sole mechanism that links place to health.<sup>25</sup>

Previous health studies have estimated the area of environmental influence using predefined administrative areas,<sup>200,201</sup> ego-centred definitions of space; such as buffers of varying distances and types around the home,<sup>199</sup> and mental maps.<sup>180,202</sup> However, the environment which individuals experience may differ substantially from these ‘residential neighbourhood’ type measures: individuals are not normally confined within these spatial boundaries, and visit an array of destinations beyond the perimeter of their residential neighbourhoods.<sup>183</sup> Having focussed exclusively on residential neighbourhoods as an area delimitation, the majority of these studies have succumb to the ‘local trap’,<sup>184</sup> resulting in a potential mischaracterisation of environmental exposure.<sup>172</sup>

The everyday movement of individuals over space between destinations, known as daily mobility, has been recognised as an important component in built environment and health research.<sup>203,204</sup> Mobility is important for identifying the shape and scale of exposure, which may vary between different population groups. For example, the proportion of travel inside and outside the neighbourhood may differ between adults and children who may interact more with their local resources and infrastructure. Mobility is also important when examining access to resources and active travel patterns.<sup>33</sup> A recent study showed adolescents living in urban areas accumulated 57% of their moderate-to-vigorous physical activity (MVPA) while commuting to activity places, rather than at the destinations themselves.<sup>26</sup>

Activity spaces have been proposed to characterise the spatial patterns of mobility.<sup>25,205</sup> These measures are thought to be more comprehensive spatial summaries of mobility and experienced space compared to traditional neighbourhood measures.<sup>25,206</sup> Activity spaces are commonly derived from convex hulls,<sup>207</sup> standard deviational ellipses<sup>191</sup> or travel time

polygons<sup>205</sup> and encompass environments both inside and outside the residential neighbourhood. Only 4% of studies in a recent review investigated both,<sup>203</sup> and these studies focused on the workplace or school, yet other activity locations and the travel between them are also of interest.<sup>25</sup> Significant differences between environmental characteristics within and beyond the neighbourhood have been shown<sup>208</sup> justifying the use of activity spaces in physical activity research.

Collecting mobility information has traditionally been burdensome for participants with the use of mobility surveys<sup>188</sup> or real-time travel diaries.<sup>189</sup> A high level of participant engagement is usually required which can lead to low compliance, incomplete and incorrect information.<sup>190</sup> Although Global Positioning System (GPS) receivers can obtain a comprehensive record of travel behaviours, long-term assessment is still hindered by technological constraints, such as signal dropout, memory limitations and poor battery life.<sup>97</sup> More recently, interactive online mapping applications with embedded questionnaires have been proposed to enhance the geographic accuracy of data, ease of collection, and the possibility of collecting additional information such as perceived spaces.<sup>33</sup> Such approaches may offer a practical solution for mobility assessment, and have shown high convergent validity when compared with GPS travel records.<sup>207,209</sup>

The Visualization and Evaluation of Route Itineraries, Travel Destinations, and Activity Spaces (VERITAS) is a web-based application delivered within a Computer-Assisted Personal Interview. VERITAS integrates interactive mapping functionality (based on Google Maps) with traditional activity and travel questions.<sup>33</sup> This enables participants to accurately geolocate destinations inside and outside of their residential neighbourhood, answer questions related to each of those destinations, and draw lines and polygons indicative of routes and spaces. VERITAS can assess mobility over extended retrospective periods, which may provide more relevant comparisons with chronic health indicators such as BMI. Online mapping techniques have yet to be trialled within an adolescent sample. The aims of this pilot study were (1) to demonstrate the feasibility and functionality of VERITAS in an adolescent sample, and (2) to compare urban form and geometric features of the perceived neighbourhood with traditional neighbourhood delimitations.

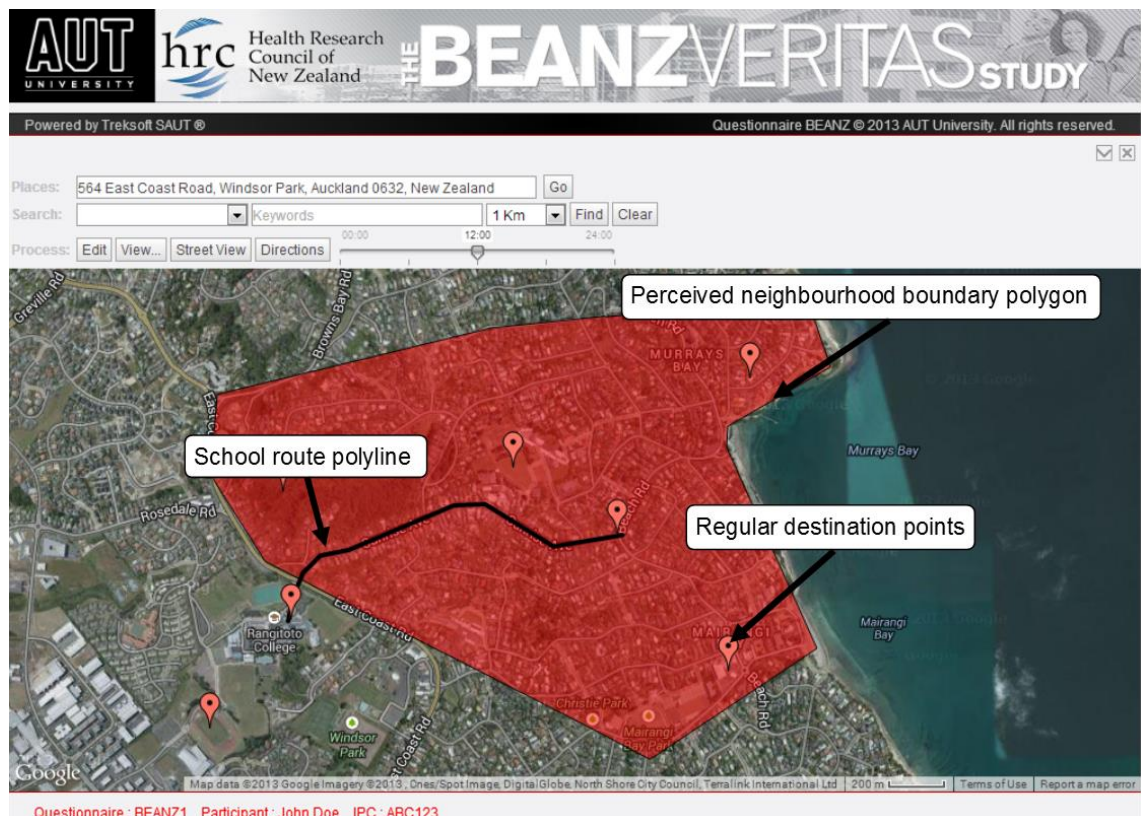
## **Methods**

### **Participants**

Twenty-eight adolescent participants (13–18 years) were recruited from an Auckland high school as a subsample of participants in the Built Environment and Adolescent New Zealanders (BEANZ) study—a cross-sectional study exploring the links between the built environment and health in New Zealand adolescents. The BEANZ recruitment procedures are described in detail elsewhere.<sup>34</sup> Briefly, New Zealand meshblock (smallest census tract unit) walkability indices were calculated for all eligible participants based on their residential addresses, which were obtained from the school's database prior to the consent process. The walkability indices used were consistent with previous research in New Zealand adults.<sup>210</sup> The subsample was selected from the pool of consenting students, with half of the sample selected from the lowest walkability tertile and the remaining half from the highest tertile in an attempt to achieve variation in built environmental exposure.<sup>210</sup> Ethical approval was granted by the Auckland University of Technology Ethics Committee (AUTEC), and written informed consent was obtained from each student and parent prior to participation.

### **Instruments**

VERITAS-BEANZ was developed by translating VERITAS-RECORD from French to English. The conception of VERITAS-RECORD is described in more detail elsewhere.<sup>33</sup> Elements of the NEWS-Y<sup>109</sup> questionnaire were incorporated and adjusted to suit adolescents in New Zealand (e.g., including netball and rugby as sporting options, and push scooters as a mode of travel option). VERITAS-BEANZ has five successive parts: (1) locating the principal residence (and secondary residence if necessary), answering questions about its occupants, and recording the level of neighbourhood attachment on a 1-6 Likert scale, (2) selecting the types of places visited in the previous six months from a list of destination categories (e.g., school, park, post office), (3) geolocating the most frequently visited destination within each of the selected destination categories, and answering questions related to that destination; such as visit frequency, mode of travel, travel companions, and whether they are allowed to go there without adult supervision, (4) plotting the usual route travelled to school by placing a series of points which connect to form a polyline, and (5) plotting their perceived neighbourhood boundary by placing a series of points, which connect to form a polygon (see Figure 3–1).



**Figure 3–1.** Google Maps tools embedded within VERITAS.

Note the data presented in this example are fictional to protect participant privacy.

Unlike VERITAS-RECORD, plotting the perceived neighbourhood boundary occurred after regular destinations had been located. It is possible that the dispersal of previously located destination markers may influence a participant’s perception of their neighbourhood, yet this order of steps was selected in hopes it would improve the accuracy of the boundary delimitation. Before plotting their perceived neighbourhood, their home was positioned at the centre of the map. Participants were then asked to “draw a shape which you feel represents your neighbourhood” and were ensured there were no right or wrong answers.<sup>211</sup>

Participants identified frequently visited destinations from a list of 33 categories extracted from the NEWS-Y questionnaire, as well as questions dedicated to sport, cultural and religious activities, and visiting friends. VERITAS-BEANZ (hereafter referred to as VERITAS) is equipped with Google Street View and embedded search tools which can identify destinations of a certain type (or from key search terms) within a given radius (Figure 3–1). Altogether, VERITAS contains a maximum of 188 individual questions (some of which may have multiple answers), although participants do not have to answer questions related to destinations they have not visited.

## **Procedure**

Data collection took place at an Auckland high school in June 2013 over a 3-day period. Height was measured to the nearest 0.1 cm using a portable stadiometer (SECA 213, Hamberg, Germany), weight to the nearest 0.1 kg using electronic scales (SECA 813, Hamberg, Germany) and waist circumference at the navel to the nearest 0.1 cm using a Lufkin Executive Thinline steel tape measure (W606PM, Cooper Hand Tools, NC, USA) in line with ISAK-developed protocols.<sup>212</sup> Trained interview technicians took each participant through VERITAS on a laptop computer which was connected to the school's Wi-Fi network. During the survey, any questions or aspects of VERITAS that participants had trouble understanding were made note of, and discussed with the research team after each data collection session. Answers and map data were automatically saved to a dedicated server during and at completion of the interview.

## **Data reduction**

### ***Destination characteristics***

VERITAS questionnaire data (mode of travel, frequency of visits, travel companions) and map data (destination, polyline, and polygon coordinates) were downloaded and imported into ArcGIS 10.1 (ESRI, Redlands, CA, USA). The shortest route between home and each mapped destination were estimated using the Network Analyst Extension and street centreline data obtained from Land Information New Zealand (LINZ; [www.linz.govt.nz](http://www.linz.govt.nz)). Using VERITAS questionnaire data, each of these estimated travel routes were coded as either active travel (i.e., walking, cycling, scooter, skateboard), passive travel (i.e., motorised transport) or mixed travel, which was defined as a combination of both passive and active travel. Visit frequency (reported as either times per week, month, or year) was converted to times per year for comparative purposes. Using the distance, frequency and mode of travel, a crude distance metric was computed to estimate the annual distance accumulated by each mode of travel for each destination type.

### ***Perceived neighbourhood comparison***

1 mile Euclidian buffers, 1 km network buffers and corresponding meshblocks were generated to illustrate similarities and differences with the perceived neighbourhood.

These buffer distances were chosen because they are commonly used in adolescent samples.<sup>123,141,143,164,213</sup> For each neighbourhood type, the distance from home to the furthest boundary vertex and the distance to the closest edge was calculated. The ratio of these two distances was used to examine how the neighbourhood was positioned around the home (a limitation of point buffers is they are always centred on the home). A measure of circularity was used to examine the general shape of perceived neighbourhoods. Circularity assesses how closely a shape resembles a circle, and is defined as the ratio of the area of a shape with the area of a circle which has the same perimeter.<sup>214</sup> Circularity was calculated using the equation:

$$Circularity = 4\pi A/P^2$$

where A is the area and P is the perimeter of the shape. The circularity ratio ranges from 0 to 1, the latter indicating a perfect circle.<sup>215</sup> For each neighbourhood, the percentage of area that overlapped the perceived neighbourhood was also calculated.

### ***Measures of urban form***

Urban form variables have been inconsistently associated with adolescent physical activity in the past,<sup>22</sup> and the different methods of representing a neighbourhood may have contributed to these discrepancies.<sup>199</sup> To examine how urban form differed across the different neighbourhoods, three measures (land use mix, street connectivity, and residential density) were calculated. Auckland Council zoning data were used to calculate land use mix. Land was categorised as residential, commercial, industrial, open space, or other. Entropy scores were used to calculate the extent of land use mix using the equation:

$$Land\ Use\ Mix = -1\left(\sum_{i=1}^n P_i * \ln(P_i)\right)/\ln(n)$$

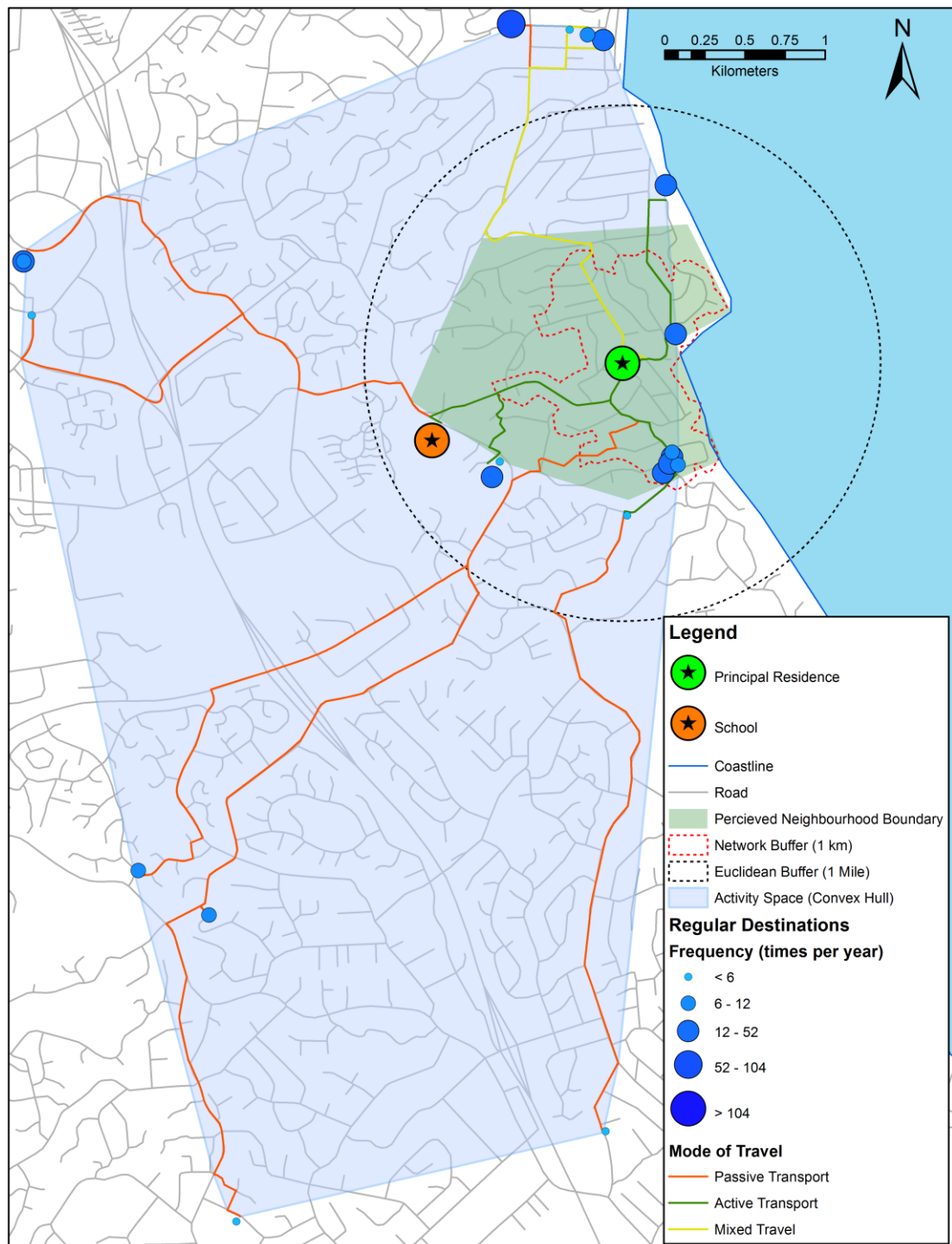
where n is the number of different land use categories and P<sub>i</sub> is the proportion of land use category i in the region. Entropy scores range from 0, which indicates no mix or homogeneous land use, to 1 which represents heterogeneous land use, or a perfect mix. Street connectivity was estimated by calculating the number of intersections with three or more intersecting streets per square kilometre. Intersections were extracted from pedestrian road network data (i.e., with non-walkable elements such as highways and on/off ramps removed). All intersections within 10 m were considered one intersection to

account for roads that may not align perfectly. As meshblock boundaries are normally defined by street centrelines, a 20-m buffer was applied to each meshblock to include peripheral intersections which may otherwise be omitted. The number of private dwellings per meshblock was obtained from the New Zealand 2006 census.<sup>68</sup> Residential density for each meshblock was calculated by dividing the total number of private occupied dwellings by meshblock area. Residential density was calculated within the other neighbourhood areas by estimating the number of private dwellings using an area weighted average based on meshblock-level data. The handling of these urban measures was consistent with previous studies.<sup>210</sup>

For the purpose of illustration, an activity space was generated from destination points using a convex hull; a minimum bounding geometry technique which encloses multiple geographic features within the smallest possible convex polygon.<sup>207</sup> Excluding rarely visited destinations may produce an activity space that more accurately resembles typical travel behaviour, but due to the pilot nature of this study, all destinations that were located during the VERITAS survey were included in the activity space delineation (see Figure 3–2).

## **Analysis**

Descriptive statistics were generated to describe participant characteristics and the amount of information collected during the VERITAS survey. Wilcoxon signed rank tests were used to assess differences between the four neighbourhood delimitations. Mann–Whitney U tests were used to assess differences between genders, and Spearman’s correlations were used to test for associations between trip distances, travel modes and travel companions. Significance was set at  $p < 0.05$ , and all analyses were conducted using IBM SPSS Statistics v22 (IBM Cooperation, USA).



**Figure 3–2.** A single participant’s VERITAS data presented in ArcGIS 10.1.

## Results

The demographic characteristics of the sample are presented in Table 3–1, and a summary of VERITAS statistics are presented in Table 3–2. In total, 529 individual destinations were located on the map (mean =  $17.9 \pm 5.11$ , range = 8–29), with similar numbers

between genders. The number of destinations that participants had visited but were unable to locate was 76, although 37% of these were from three participants who were unfamiliar with interpreting maps. The time taken to complete the survey averaged  $28.3 \pm 9.40$  min, and was significantly correlated with the number of destinations located ( $r = 0.61$ ,  $p < 0.01$ ). Overall, 41% of visited destinations were inside the perceived neighbourhood boundary, with females showing a slightly higher percentage than males (44.7 and 38.5%, respectively), although this difference was not significant ( $p = 0.56$ ). The level of neighbourhood attachment (mean =  $4.39 \pm 1.13$ ) was unrelated to the number of destinations that fell inside the perceived neighbourhood ( $r = 0.11$ ,  $p = 0.57$ ) or its area ( $r = -0.08$ ,  $p = 0.70$ ).

**Table 3–1.** Participant demographic characteristics.

	Male n = 14	Female n = 14	All n = 28
Age	15.8 $\pm$ 1.49	15.9 $\pm$ 1.53	15.9 $\pm$ 1.48
Height (cm)	174 $\pm$ 7.87	165 $\pm$ 4.78	169 $\pm$ 8.07
Weight (kg)	61.9 $\pm$ 9.80	57.5 $\pm$ 8.13	59.7 $\pm$ 9.12
BMI (kg·m <sup>-2</sup> )	20.3 $\pm$ 2.48	21.2 $\pm$ 2.42	20.8 $\pm$ 2.44
Waist circumference (cm)	72.6 $\pm$ 7.09	67.6 $\pm$ 5.12	70.1 $\pm$ 6.6

Data are presented as mean  $\pm$  SD.

BMI = Body Mass Index.

**Table 3–2.** VERITAS descriptives by sex.

	Male n = 14	Female n = 14	All n = 28
Time to complete VERITAS (min)	30.7 ± 11.6 (13.3 – 64.8)	25.8 ± 6.10 (16.8 – 42.8)	28.3 ± 9.44
Number of destinations geolocated	17.5 ± 5.50 (8 – 27)	18.29 ± 4.86 (13 – 29)	17.9 ± 5.11
Destinations inside perceived neighbourhood (%)	38.5 ± 31.2 (0 – 90)	44.7 ± 23.4 (0 – 81)	41.6 ± 27.2
Neighbourhood attachment (1–6 Likert scale)	4.21 ± 1.25 (2 – 6)	4.57 ± 1.02 (2 – 6)	4.39 ± 1.13
Number of people living at address	4.43 ± 1.16 (3 – 7)	4.00 ± 1.30 (2 – 6)	4.21 ± 1.23

Data are presented as mean ± SD (min – max)

Table 3–3 shows the characteristics of each type of destination. On average, the closest destinations to home were public parks ( $0.89 \pm 0.88$  km), public transit stops ( $1.37 \pm 2.68$  km), schools with recreation facilities ( $1.47 \pm 1.17$  km), and convenience stores ( $1.48 \pm 1.01$  km). These four destinations also had the highest proportion of active travel trips (88.2, 81.0, 54.5, and 56.0% respectively). Overall, distance to destinations was positively associated with passive travel ( $r = 0.68, p < 0.01$ ), negatively associated with active travel ( $r = -0.63, p < 0.01$ ), and negatively associated with traveling alone ( $r = -0.46, p < 0.05$ ). The distance accumulated per year metric shows the relative importance of each destination for each mode of travel (although it assumes trips are made from home and thus ignores trip chains). Across the whole sample, the most active (457 km), passive (1067 km), and mixed (611 km) transport distance was accumulated during the commute to and from school. Passive transport distance was also high when travelling to organised sport (669 km) and indoor recreation facilities (634 km), whereas active transport distance was high when travelling to playing fields (291 km), public transit stops (257 km), and friends' houses (167 km). Public open spaces and cultural or religious activities also had high active transport distances, although only one third of participants visited these types of destinations. Being allowed to travel to a destination without adult supervision was positively associated with traveling alone ( $r = 0.61, p = 0.01$ ) and having friends as travel companions ( $r = 0.64, p < 0.01$ ), but negatively associated with passive travel ( $r = -0.50, p < 0.01$ ). Active travel was positively associated with traveling with friends ( $r = 0.53, p < 0.01$ ), siblings ( $r = 0.43, p < 0.05$ ) and alone ( $r = 0.55, p < 0.01$ ), but negatively associated with adults ( $r = -0.71, p < 0.01$ ).

**Table 3–3.** Geolocated destination characteristics.

Destination	Network Distance (km)	Visited (%)	Frequency (times/year)	Mode of Travel (%)			Weighted Distance (km/year) <sup>a</sup>			Without adults (%)	Travel Companions (%)			
				Active	Passive	Mixed	Active	Passive	Mixed		Friends	Siblings	Parent	Alone
Own School	4.09 ± 3.84	100	261 ± 10	21.4	50	28.6	457	1060	611	96.4	71.4	42.9	14.3	32.1
Playing Fields & Courts	3.59 ± 5.94	50.0	81 ± 57	50	50	0	291	291	0	100	57.1	28.6	42.9	42.9
Public Open Space	9.49 ± 8.47	32.1	32 ± 49	44.4	33.3	22.2	270	202	135	88.9	77.8	44.4	44.4	0
Public Transit Stop	1.37 ± 2.68	75.0	116 ± 109	81	14.3	4.8	258	45.5	15.3	100	57.1	33.3	9.5	57.1
Cultural or Religious	3.58 ± 2.78	35.7	113 ± 111	30	60	10	243	486	80.9	-	50	20	40	50
Visiting friends	1.76 ± 2.31	82.1	91 ± 70	52.2	26.1	26.1	167	83.6	83.6	-	30.4	21.7	26.1	65.2
Beach or Lake	3.63 ± 5.9	75.0	45 ± 35	47.6	33.3	19	156	109	62.1	95.2	81	33.3	66.7	33.3
Swimming Pool	6.84 ± 5.87	39.3	42 ± 49	18.2	72.7	9.1	105	418	52.3	81.8	27.3	45.5	72.7	9.1
Sport	4.93 ± 6.17	82.1	120 ± 68	8.7	56.5	34.8	103	669	412	-	56.5	30.4	52.2	21.7
Indoor Recreation	4.33 ± 4.19	57.1	90 ± 60	12.5	81.3	6.3	97.4	634	49.1	81.3	25	18.8	37.5	31.3
Basketball Court	2.41 ± 2.95	26.8	50 ± 37	37.5	50	12.5	90.4	121	30.1	87.5	75	62.5	25	25
School with Recreation Facilities	1.47 ± 1.17	39.3	56 ± 52	54.5	36.4	9.1	89.7	59.9	15.0	100	90.9	54.5	0	18.2
Public Park	0.89 ± 0.88	60.7	49 ± 32	88.2	0	11.8	76.9	0	10.3	100	76.5	35.3	29.4	35.3
Convenience Store	1.48 ± 1.01	89.3	42 ± 33	56	28	16	69.6	34.8	19.9	96	48	36	24	48
Any Other School	1.97 ± 1.80	39.3	26 ± 36	50	28.6	21.4	51.2	29.3	21.9	100	64.3	42.9	35.7	35.7
Fast Food	4.17 ± 5.00	82.1	31 ± 31	17.4	60.9	21.7	45.0	158	56.1	82.6	52.2	34.8	65.2	13
Walking Trails	2.29 ± 2.18	32.1	19 ± 33	44.4	55.6	0	38.6	48.4	0	55.6	33.3	55.6	88.9	11.1
Café	4.59 ± 4.41	78.6	24 ± 24	9.1	63.6	27.3	20.1	140	60.2	95.5	54.5	31.8	63.6	4.5
Video or DVD Store	2.05 ± 1.29	71.4	32 ± 24	15	40	45	19.7	52.5	59.0	100	55	35	75	25
Supermarket	2.29 ± 1.29	96.4	57 ± 35	7.4	59.3	33.3	19.3	155	86.9	92.6	18.5	37	81.5	7.4
Chemist	1.84 ± 1.43	67.9	22 ± 27	21.1	47.4	31.6	17.1	38.4	25.6	63.2	5.3	21.1	89.5	15.8
Bank	2.88 ± 1.52	82.1	18 ± 13	8.7	65.2	21.6	9.02	67.6	22.4	69.6	4.3	13	87	30.4
Restaurant	4.18 ± 4.76	71.4	17 ± 11	5	75	20	7.11	107	28.4	65	40	40	95	0
Post Office	2.85 ± 1.94	46.4	11 ± 9	7.7	69.2	23.1	4.83	43.4	14.5	69.2	0	23.1	84.6	15.4
Clothing Store	5.42 ± 3.22	82.1	36 ± 30	0	87	13	0	340	50.7	95.7	73.9	30.4	69.6	26.1
Bookstore	4.48 ± 2.82	39.3	30 ± 60	0	81.8	18.2	0	220	48.9	100	27.3	27.3	100	18.2
Library	4.39 ± 2.89	64.3	12 ± 8	0	77.8	22.2	0	82.0	23.4	94.4	44.4	16.7	55.6	27.8
Laundry	3.85 ± 0	3.60	1 ± 0	0	100	0	0	7.70	0	0	0	0	100	0

Data presented as mean ± SD unless otherwise stated.

Destinations are ordered by active travel distance per year (most to least).

<sup>a</sup>Weighted distance = ((network distance × 2) × frequency) × (mode of travel ÷ 100).

Table 3–4 compares urban form characteristics and geometric features assessed within each neighbourhood delimitation. On average, the perceived neighbourhood boundary area ( $3.54 \pm 2.64 \text{ km}^2$ ) was larger than NZ meshblocks ( $0.12 \pm 0.16 \text{ km}^2$ ) and a 1 km network buffer ( $1.03 \pm 0.33 \text{ km}^2$ ), but smaller than a 1 mile Euclidean buffer ( $8.14 \pm 0 \text{ km}^2$ ). The proportion of area which fell inside the perceived neighbourhood boundary was highest in meshblocks (85.1%) followed by the 1 km network (79.4%) and 1 mile Euclidean buffers (34.6%). The distance to the furthest boundary vertex was considerably longer than the distance to the closest edge, and the ratios between these distances were similar in all neighbourhood delimitations apart from the 1 mile Euclidean buffer (which has perfect shape uniformity). The perceived neighbourhood boundary showed greater circularity ( $0.69 \pm 0.15$ ) than meshblocks ( $0.53 \pm 0.15$ ) and 1 km network buffers ( $0.0 \pm 0.0$ ). The urban form characteristics varied substantially between each neighbourhood, although residential density and street connectivity were similar between the 1 km network buffer and the perceived neighbourhood.

**Table 3–4.** Neighbourhood geometry and urban form comparison

	VERITAS Perceived Neighbourhood	NZ Meshblock	1 mile Euclidian Buffer	1km Network Buffer	Activity Space (convex hull)
Area (km <sup>2</sup> )	3.54 ± 2.64	0.12 ± 0.16**	8.14 ± 0	1.03 ± 0.33**	19.7 ± 24.8
Perimeter (km)	7.38 ± 3.38	1.57 ± 0.90**	10.1 ± 0	5.98 ± 1.45**	19.6 ± 10.9
Home to furthest boundary edge (km)	2.44 ± 1.38	0.53 ± 0.37**	1.61 ± 0	0.9 ± 0.09**	6.77 ± 4.3
Home to closest boundary edge (km)	0.54 ± 0.39	0.05 ± 0.04**	1.61 ± 0	0.18 ± 0.11**	0.36 ± 0.31
Farthest to closest edge ratio	10.9 ± 13.3	14.44 ± 12.55	1.0 ± 0	13.5 ± 27.2	26.1 ± 24.5
Neighbourhood circularity	0.69 ± 0.15	0.53 ± 0.15**	1.0 ± 0	0 ± 0**	0 ± 0
Perceived neighbourhood overlap (% area) <sup>a</sup>	-	85.1 ± 27.4	34.6 ± 21.7	79.4 ± 27.1	25.2 ± 23.5
Land Use Mix (entropy score)	0.38 ± 0.21	0.22 ± 0.16*	0.47 ± 0.15*	0.29 ± 0.12**	0.60 ± 0.16
Residential Density (dwellings/km <sup>2</sup> )	808 ± 234	894 ± 321**	627 ± 181**	854 ± 200	674 ± 189
Connectivity (intersections/km <sup>2</sup> )	45.4 ± 17.9	23.71 ± 23.7**	59.9 ± 21.2**	41.0 ± 7.70	52.0 ± 11.4

Data presented as mean ± SD.

<sup>a</sup>Calculated as the percentage of each neighbourhood's area that fell inside the perceived neighbourhood boundary.

\*Significantly different from perceived neighbourhood (p < 0.05).

\*\*Significantly different from perceived neighbourhood (p < 0.01).

## Discussion

Although the built environment has been shown to contribute to young people's activity and health behaviours,<sup>17,216</sup> current evidence is inconsistent and exactly how the environment exerts its influence remains largely unclear.<sup>22,217</sup> Accounting for mobility and destinations beyond the residential neighbourhood have been identified as important elements to further our understanding of the environment-health relationship.<sup>25,183</sup> This pilot study sought to demonstrate VERITAS as an innovative online mapping method to assess mobility patterns and perceived spaces in adolescents.

Our results indicate that locating destinations of interest on an electronic map were relatively straightforward for most participants regardless of gender and age. The interview technician's local area knowledge proved to be beneficial when helping participants locate destinations, especially individuals who were not accustomed to reading maps. The search tools embedded within VERITAS were useful when participants knew the name of the destination and an approximate location, but were unable to pinpoint the destination itself. It was found that displaying the map using a hybrid view (i.e., a satellite view superimposed with roads and street names) assisted participants in pointing out familiar landmarks (such as treed areas and clusters of buildings) that were not visible on a simple street map (Figure 3–1). The online mapping methodology performed in this study closely resembles the SoftGIS methodology developed by Kytä and colleagues<sup>218,219</sup> in Finland. These approaches focus more on the collection of geographically referenced 'soft' information which takes into consideration an individual's experiences, motivations, and perceptions. When combined with traditional GIS data layers, this type of information has been a welcome addition to evidence-based planning.<sup>220,221</sup> Their work has led to a better understanding of children's meaningful places and independent mobility.<sup>219</sup>

Table 3–3 shows that certain destinations feature more regularly within adolescent's daily routines (e.g., own school, sporting activities) while others afford a higher proportion of active travel trips (e.g., public parks, public transportation services, friends' houses). Identifying these travel patterns is not only relevant for examining what destinations are important for adolescent mobility and physical activity, but because the importance of these destinations may vary for other population groups. For example, the establishment of recreation facilities (e.g., basketball court) may be more pertinent for younger groups as opposed to older adults. Our results also demonstrate that destinations closer to home

(i.e., public parks), have a higher proportion of active transport trips, which is consistent with current literature; distance is one of the strongest predictors of active transportation in young people.<sup>222,223</sup> Being allowed to travel without adult supervision and with friends or siblings was also associated with greater active travel, alluding to the importance of independent mobility and social components of adolescent travel. Although parental willingness for independent travel is affected by crime and other safety factors,<sup>222</sup> parents may be prone to allow greater independent mobility when destinations are closer to home, which translates into greater active travel.

The results presented in Table 3–4 show the perceived neighbourhood is not uniform in all directions, which highlights the limitation of circular buffers which are derived from fixed radial distances around the home.<sup>199</sup> These data also suggest that the distance from the residence to the edge of the neighbourhood is not the only variable to consider, but also the shape and positioning of the neighbourhood around the home. Network buffers can somewhat overcome this problem by accounting for environmental barriers and hazards along the street network, yet 20% of the 1 km network buffer fell outside the perceived neighbourhood. Although the chosen buffer size would have contributed to this discrepancy, network buffers cannot account for destination preferences or the spatial distribution of local resources and amenities around the home, which likely influence the shape of experienced space.

More than half of all visited destinations (58%) were beyond the bounds of the perceived neighbourhood. The space someone perceives as their neighbourhood might closely resemble the areas that are reached on foot; an individual may feel a higher level of attachment to these environments as they are experienced more intimately. The perceived neighbourhood represented just over a quarter of the total activity space area. The reality is many adolescents are not restricted to their neighbourhoods during daily living, and can use passive methods of transportation to access destinations beyond their neighbourhood limits. Capturing the totality of visited destinations can be used to determine an individual's accessibility to amenities, and how these levels of access translate into physical activity. Improving the precision of built environment measures may reduce the probability of type 2 errors.

Table 3–4 demonstrates that measures of urban form differ between each of the neighbourhood delimitations, suggesting the presence of the modifiable areal unit problem; these environmental variables are sensitive to the spatial unit used for

aggregation.<sup>177</sup> It has been suggested that a strong behavioural justification is needed when deciding how the neighbourhood construct is represented spatially<sup>178</sup> and the interaction between an individual and their environment must be taken into account. A recent GPS-based study found that adolescent's self-identified neighbourhoods were not significantly different in area from census-defined neighbourhoods, but the self-identified neighbourhoods were shown to better capture environments where adolescents spent their time and engaged in MVPA.<sup>211</sup> However, a perceived neighbourhood is essentially a socially-derived construct, and future work is needed to understand what these shapes represent in reality.

### **Study limitations**

Although activity spaces may be a step forward in this field,<sup>25</sup> and despite the crude activity space demonstration in this study, the area within convex activity-space polygons may contain environments an individual does not encounter.<sup>33</sup> Buffering individual destinations and routes between these destinations may more closely reflect true interaction with the environment.<sup>205,224</sup> The development of domain specific activity spaces (e.g., green space or foodscape exposure)<sup>225</sup> or travel mode activity spaces (e.g., active transport activity space) by circumscribing destinations and routes that are associated with that domain, or travelled to by that mode, may help to isolate environmental effects on the variable of interest. As this was a pilot study with a small sample size, all inferences must be taken with caution.

### **Conclusion**

Capturing mobility behaviours and travel to non-residential destinations has been identified as an avenue of progression in this field. This pilot study demonstrated the functionality of the VERITAS online mapping survey, and the feasibility of delivering this survey in an adolescent sample. These methods provide an interface to gather mobility information, and may help to overcome the limitations of previous work. These data show great promise for understanding the types of destinations that adolescents frequent; however, further work is required to understand the utility of perceived neighbourhood spaces, and how destination information can be operationalised and integrated into physical activity research.

## **Chapter 4 - Adolescent school travel: is online mapping a practical alternative to GPS-assessed travel routes?**

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### **Preface**

The preceding chapter described and piloted the VERITAS survey, illustrating the novelty of destinations and perceived neighbourhood spaces. Chapter 4 presents the second VERITAS methodology paper by examining the accuracy of the VERITAS route drawing capabilities. The introductory chapters in this thesis suggested the mode share of active travel trips has been steadily declining, and certain features of travel routes, such as pedestrian infrastructure and traffic volume, may be related to travel decisions. Previous work has attempted to link mode of travel with route characteristics, but obtaining precise route information is challenging. This paper examines the spatial agreement between VERITAS-drawn and GPS-assessed school routes highlighting factors associated with the strength of agreement. The paper from this chapter was accepted in October 2016 for publication in the upcoming ‘Walking and Walkability’ Special Issue in the *Journal of Transport and Health*, and is currently in press (Appendix D).

## Abstract

**Background:** Geographically accurate travel routes are necessary to estimate exposure to the environment and its potential influence on travel behaviour. Although assessing travel behaviours with Global Positioning System (GPS) receivers is increasingly common, these protocols place noticeable burden on participants and processing these data is time consuming and error-prone. Interactive online mapping surveys allow users to draw their own travel routes, and may offer a time and cost-effective alternative; however, these routes are still self-reported, and their true accuracy remains unknown.

**Methods:** A total of 196 adolescents drew their usual route to school within an online mapping survey and wore a GPS receiver for 7 days. Individual home-to-school routes were extracted from GPS data. Generalized linear mixed models were used to assess differences in distance and spatial agreement (overlap) between routes, and how these varied by mode of travel and other route characteristics.

**Results:** GPS-assessed routes were longer than the routes participants drew across all travel modes. Routes travelled actively displayed 12.32% higher spatial agreement compared to those travelled passively ( $p < 0.01$ ). Taking multiple routes to school (29.9% of participants) reduced the agreement by 10.76% ( $p < 0.01$ ). Every additional travel mode transition (e.g., during multimodal trips) was associated with 2.20% lower agreement ( $p < 0.01$ ). Interestingly, 40.7% of participants used more than one travel mode to school over the assessment period.

**Conclusions:** Online mapping surveys are a feasible method for route assessment in adolescents, particularly for active travel routes. With the integration of survey questions, there is considerable potential for understanding the intricacies of travel behaviours. However, the self-reporting error seems more pronounced for longer routes, and when multiple travel modes are used. Researchers should consider the advantages (e.g., ease of collection) and disadvantages (e.g., lack of temporal information) when deciding if the data obtainable are sufficient to answer their research questions.

## Introduction

Regular physical activity is important for maintaining health and wellbeing,<sup>53</sup> and engaging in active transportation (commuting via walking or cycling) is an effective means for accumulating physical activity over the course of a day.<sup>226</sup> In young people, active transportation is also important for other aspects of health and development, such as improved navigational skills,<sup>227</sup> the ability to evaluate and manage risk,<sup>14</sup> and a higher sense of belonging through interaction with people and their local community surroundings.<sup>172,228</sup> Despite this, the mode share of active travel school trips has been steadily declining,<sup>229</sup> and evidence suggests that built environment factors such as pedestrian infrastructure, traffic volume, and perceived pedestrian safety may be related to travel decisions.<sup>230,231</sup> As such, previous research has attempted to link mode of travel with environmental characteristics along travel routes.<sup>232-234</sup> Quantifying actual travel routes is important, as theorised influences on travel behaviour can be misclassified when predicted routes are used.<sup>235,236</sup> These discrepancies could misguide planning or policy interventions by targeting environmental factors that have no influence on school travel decisions.<sup>237</sup>

The use of geographic information system (GIS) software to calculate the shortest possible route has been common in previous physical activity and travel studies due to the ease of its computation.<sup>232-234</sup> However, the use of Global Positioning System (GPS) receivers to assess travel patterns is becoming more prominent because of their objectivity and spatial accuracy. Previous research has illustrated that the degree of spatial agreement between the shortest route and GPS-derived travel routes can vary substantially, and the deviation from the shortest route may be related to the presence or absence of shops and services, traffic volume, and other environmental features.<sup>119,236,238</sup> Although it is becoming easier to derive travel information from GPS data<sup>103,193,239</sup> there are still practical problems associated with GPS data collection; namely cost, participant burden, signal degradation, battery life, non-compliance, and memory limitations.<sup>240</sup>

Interactive online mapping applications are another emerging method for collecting spatial information. These techniques enable users to report information geographically, and have been designed to allow non-experts to use their local knowledge and experiences to inform urban planning and decision-making processes.<sup>220</sup> Internet-delivered mapping systems have received increased attention, particularly due to the widespread utilisation and integration of Google Maps technology.<sup>241</sup> Although printed paper maps have been

used to collect route information previously,<sup>237,242,243</sup> online mapping techniques offer several advantages as recall may be stimulated through map interaction (e.g., controlling zoom or overlaying satellite imagery). Both children and adults have used online mapping applications to draw their travel routes to destinations.<sup>32,33</sup>

These techniques may provide a cost-effective alternative to GPS-based route assessment, as information can be collected in a quick and efficient manner, and researchers can avoid the collection and processing problems associated with GPS data. There is also considerable potential for integrating survey questions to capture perceptions or preferences about travel routes, which has been recommended to help unravel the complexities of travel decisions.<sup>244</sup> Although routes drawn by participants have a high possibility of being representative of actual routes travelled, they are still self-reported, and hence the true accuracy of these routes remains uncertain. The aims of this study were (1) to assess the spatial agreement between GPS-assessed routes to school and those drawn by participants within an online mapping survey, and (2) to determine if spatial incongruency (if any) is related to mode of travel and other route characteristics.

## **Methods**

### **Participants**

A total of 196 adolescents (12–18 years old) participated in this study. All participants were part of a larger sample recruited for the Built Environment and Adolescent New Zealanders (BEANZ) study: a cross-sectional study exploring the links between the built environment and health in New Zealand adolescents. The BEANZ recruitment procedures are described in more detail elsewhere.<sup>34</sup> The subsample used in this study consisted of approximately 30 participants from each of seven schools situated throughout Auckland and Wellington cities, located on the North Island of New Zealand. Ethical approval was granted by the Auckland University of Technology Ethics Committee. Written informed consent was obtained from each parent and assent from each student prior to participation.

## **Instruments**

### ***VERITAS***

The online mapping application used in this study was VERITAS (Visualisation and Evaluation of Route Itineraries, Travel destinations and Activity Spaces), a web-based interactive mapping survey which integrates Google Maps with physical activity and travel questions. VERITAS-BEANZ was designed specifically for the BEANZ study, and its development is described elsewhere.<sup>245</sup> Briefly, VERITAS-BEANZ was conceived by translating VERITAS-RECORD<sup>33</sup> from French to English, and modifying it for use with an adolescent sample by incorporating elements of the NEWS-Y<sup>109</sup> questionnaire. Embedded mapping tools allow participants to plot points, draw lines and polygons that represent destinations, travel routes and spaces, respectively. Additional information about each of these mapped features can be collected, such as travel companions, mode of travel, or frequency of visits. Routes are created by placing a series of points on the map, which are visually connected with a line (see Figure 4–1). If a participant makes a mistake, there is an undo button which removes the last point that was placed. Routes are editable by clicking a previously placed point, and dragging it to a new location. Standard Google Maps functionality enables the user to zoom in or out, make use of Google Street View, and set the base map as either a simple road map, satellite imagery, a terrain map, or a hybrid of the above.

### ***GPS receiver***

Each participant was fitted with a QStarz BT-Q1000XT GPS receiver. This commercially available device is one of the most widely used in the field, and has shown high accuracy when assessing several modes of transportation in varying environmental conditions.<sup>246</sup> The device was initialised to record at a 15-s epoch using QTravel (v1.46, Taipei, Taiwan). Apart from recording positional information (latitude and longitude), the signal-to-noise ratio (SNR) was also recorded to assist with the automated data cleaning process (see data reduction below).



**Figure 4–1.** An example route drawn in the VERITAS online mapping interface.

These data are fictional to protect participant privacy.

## Procedure

Data collection for the BEANZ study took place between February 2013 and September 2014. Trained research assistants supervised each participant when completing VERITAS on a laptop computer, and provided assistance if needed. Participants were asked to locate their home, and plot their usual travel route to school. They were then asked who their usual travel companions on the school journey were, and whether this was the only route they took to school. Answers and map data were saved to a dedicated server during and at the completion of the survey. Participants were then fitted with the GPS receiver, which was placed in a small pouch and attached to their waist via an elastic belt. An Actigraph GT3X accelerometer (Actigraph, Pensacola, FL) was placed alongside the GPS receiver to calculate device wear time.<sup>247</sup> Each participant was taught how to wear the equipment and how to charge the GPS receiver before they went to sleep each night. Eight days later, the equipment was collected from the school, and each participant received a shopping mall voucher to thank them for participating.

## **Data reduction**

### ***VERITAS route***

VERITAS survey data were downloaded from our server and imported into ArcGIS 10.2.1 (ESRI, Redlands, CA, USA). Home-to-school routes were generated using the point-to-line tool, and were visually inspected for errors.

### ***GPS routes***

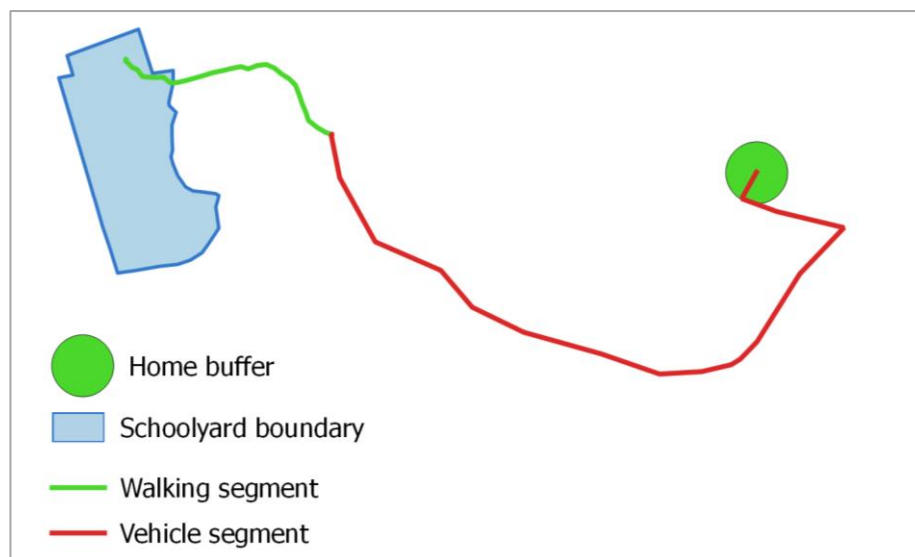
#### ***PALMS***

Raw GPS and accelerometer data were processed using the Personal Activity Location Measurement System (PALMS; <https://ucsd-palms-project.wikispaces.com>). PALMS is a web-based application developed by researchers at the University of California, San Diego, and is designed to clean and merge multiple timestamped data streams (e.g., GPS, accelerometer and heart rate data). Invalid GPS points were identified based on large, rapid changes in speed and elevation, and were replaced by imputing coordinates of the last known valid fix. Using a set of classification algorithms, individual trips were identified based on a set of user-defined criteria; sequential fixes accumulated over a period of at least 2 min that spanned at least 100m. Pauses of up to 3 min were permitted to account for routine stoppages during the trip (e.g., traffic lights, road crossings). Device wear time was calculated by removing all periods where the accelerometer recorded zero counts for at least 60 min, as recommended by previous research.<sup>247</sup>

Each GPS point was categorised as indoors or outdoors based on the signal-to-noise ratio. All points with a sum SNR of less than 225 were considered indoor points, and these were removed from the beginning and end of all trips. Each trip trajectory was assigned the appropriate mode of travel based on speed; minimum speeds were 35 km/h for vehicle, 10 km/h for bicycle, and 1 km/h for walking, where the 90th percentile of speeds along the trip were considered. PALMS trip detection and mode of travel estimation has been shown to have reasonably high accuracy when using these parameters.<sup>248</sup>

A custom-designed PostgreSQL (<http://www.postgresql.org>) database that utilised the PostGIS extension (<http://postgis.net>) was employed to automatically recognise and extract individual home-to-school trips from the cleaned GPS data retrieved from PALMS. Firstly, multimodal trips were built from PALMS output data by checking if two sequential trips met a spatial and temporal criterion: (1) the start point of the trip was within 200 m of the end point of the previous trip, and (2) the start time of the trip was within 10 min of the previous trip's end time. Segments that were identified as being part of the same trip were then merged into a new trip trajectory (e.g., a public transit trip could contain walk-vehicle-walk segments). The number of segments that made up a trip was preserved as an attribute. Secondly, a 50m Euclidean buffer of each participant's home point, and a boundary of each schoolyard digitised in ArcGIS were added to the database. Lastly, spatial queries were used to extract trips that started inside the home buffer and ended inside the schoolyard polygon (see Figure 4–2).

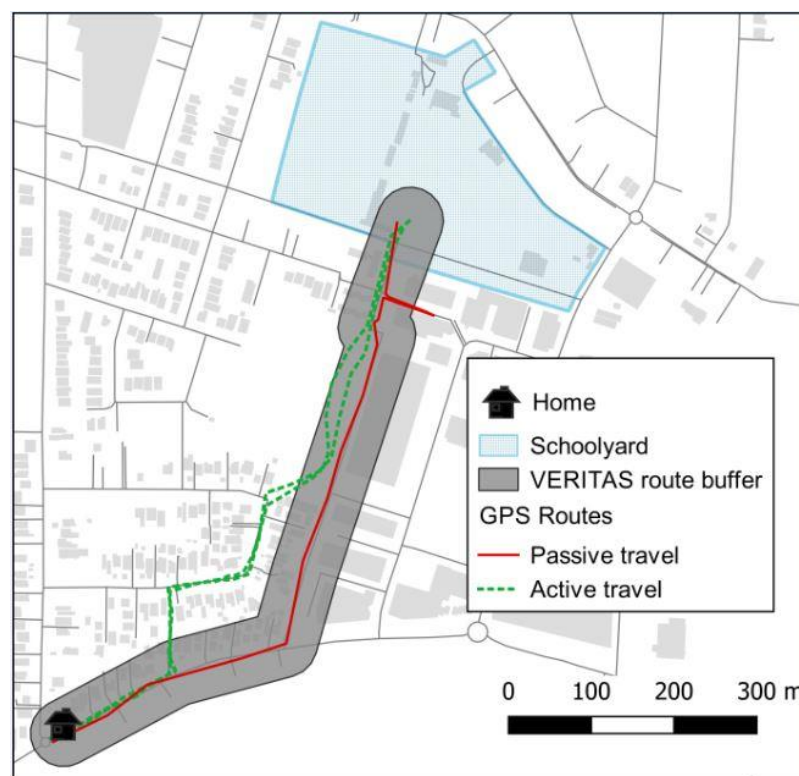
All trips that consisted of walking or cycling segments were categorised as active travel trips, whereas those that only consisted of vehicle segments were categorised as passive travel trips. All trips that had a mixture of vehicle and walking or cycling segments (such as using public transit) were categorised as mixed travel. This approach was taken knowing the importance of public transit use on physical activity and body size,<sup>249</sup> and to allow the detection of school trips with pauses longer than the 3 min (i.e., waiting at a bus station). Walking and cycling were not separated as less than 4% of total trips were by bicycle.



**Figure 4–2.** Illustration of a vehicle-walk multimodal school trip from GPS data

### Calculation of spatial agreement

Within the PostgreSQL database, a function was developed to estimate the percentage of spatial agreement between two routes. A 50-m buffer was applied to each VERITAS route, and the percentage of each GPS route that fell inside this buffer was calculated using a spatial intersection (see Figure 4–3). The distance of 50-m was selected to account for road width, GPS signal inaccuracies, and to encompass the footpath on both sides of the road. A 50-m buffer has been used successfully in previous route comparison studies.<sup>236,238</sup>



**Figure 4–3.** Illustration of VERITAS and GPS-assessed route comparison.

### Calculation of route characteristics

Street centreline data obtained from Land Information New Zealand (LINZ; [www.linz.govt.nz](http://www.linz.govt.nz)) was used to identify road hierarchy. Roads were categorised as either residential roads, collector roads, arterial roads, principal or major highways. The percentage of each route which fell on residential roads was computed in ArcGIS as a proxy for low traffic volume and speed. Route elevation was calculated from topographic isolines using the Path Slope tool, which is part of the ArcGIS Military Analyst toolbox. Each route polyline was split into a number of segments and the slope of each segment

was calculated. A slope of 5% is a common threshold in cycle path planning policy,<sup>250</sup> and has been used in cycling behaviour research.<sup>251-253</sup> In theory, people may be more tolerant to a 5% slope while walking compared to cycling, especially in a city such as Auckland, so the percentage of the route which fell on a slope of less than 8% (equivalent to a 4.57° incline, or a rise-to-run ratio of 1:12.5) was calculated. Two binary variables were created from additional VERITAS route information: if they normally travelled to school with their friends, and if the route they drew was the only route they took to school. The proportion of each route that did not fall on a road (i.e., outside a 50m buffer of the street centreline) was also calculated.

### **Statistical Analysis**

Data were initially checked for normality, which revealed all variables were not normally distributed. As such, descriptive statistics in the form of the median and interquartile range were computed. Differences between VERITAS and GPS route characteristics were tested using Wilcoxon signed-rank tests, and Kruskal-Wallis H tests (with Dunn-Bonferroni post hoc comparisons) were used to assess differences between the three travel modes. A series of three-level generalized linear mixed models using the identity link were developed to assess which route characteristics predicted the degree of spatial agreement, and the difference in distance, between the VERITAS and GPS routes. This approach was taken to account for the clustering of routes within individuals within schools.<sup>254</sup> Routes formed the repeated measure, and school\*person was added as a 2-way random effect with unstructured covariance. A correlation matrix of all potential predictor variables was generated to test multicollinearity before inclusion into the model.<sup>255</sup> None of the following variables were highly correlated, and were therefore taken forward to model building as fixed effects: route distance, mode of travel, number of GPS trip segments, percentage of the GPS route that fell off-road, and whether they took multiple routes to school. Model fit was assessed using Bayesian Information Criterion. Pairwise comparisons for categorical factors (i.e., mode of travel) were assessed using the sequential Bonferroni adjustment while holding the means of continuous data constant. Significance was set at  $p < 0.05$ , and all analyses were conducted using IBM SPSS Statistics v23 (IBM Cooperation, USA).

## Results

In total, 191 participants provided GPS data, with 12,083 individual trips (inclusive of multimodal trips) detected over the seven-day measurement period. Of these, 167 participants (101 male) had at least one home-to-school trip that was automatically recognised, with 595 individual home-to-school trips recognised in total (an average of 3.56 home-to-school trips per person). There were no differences in age, VERITAS route distance or gender between included participants and those with no home-to-school trips (assessed via independent-samples t-test or chi-square where appropriate). However, the number of weekdays with at least 10 hours of device wear time was higher for included participants (3.65, SD = 1.16) compared to those who were excluded (2.0, SD = 2.4;  $p < 0.01$ ). The mean (SD) age of included participants was 14.99 (1.25) years.

Overall, 259 school trips were categorised as active travel, 68 as passive travel, and 242 as mixed travel; 25 home-to-school trips were excluded because they did not occur on weekdays. Interestingly, 99 participants (59.3%) used the same mode of travel for all their school trips, while 58 (34.7%) used two different modes, and 10 (6%) used all three. Similarly, 50 participants (29.9%) reported they took more than one route to school during the VERITAS survey. The median school travel time assessed by the GPS was 22.8 min, and differed significantly by travel mode, with 20.5, 9.3, and 27.5 min for active, passive and mixed travel, respectively (all pairwise contrasts  $p < 0.01$ ).

Table 4–1 presents the differences in route characteristics categorised by route assessment method and travel mode. The median GPS route distance was slightly longer than the VERITAS route distance, which persisted for all travel modes. The share of the route that fell on a slope of less than 8% also differed between GPS and VERITAS for active travel, but not for passive or mixed travel routes. A larger proportion of the GPS routes fell off-road for all travel modes, and overall. The median proportion of the GPS routes that fell on residential roads was similar to VERITAS routes for active and passive travel, but differed for mixed travel.

**Table 4–1.** Differences in route characteristics by measurement method and travel mode.

		GPS Routes	VERITAS Route	<i>p</i> <sup>a</sup>
Route distance (km)	All	<b>3.14 (1.76, 6.34)</b>	<b>2.41 (1.29, 5.67)</b>	<b>&lt; 0.001</b>
	Active	<b>1.74 (1.08, 2.55)</b>	<b>1.4 (0.91, 2.03)</b>	<b>&lt; 0.001</b>
	Passive	<b>3.36 (2.37, 6.07)</b>	<b>2.45 (1.62, 5.51)</b>	<b>0.001</b>
	Mixed	<b>6.51 (3.63, 13.3)</b>	<b>5.68 (2.96, 13.54)</b>	<b>&lt; 0.001</b>
8% slope or less (% of route)	All	<b>83.3 (70.9, 99.3)</b>	<b>83.9 (68.5, 98.8)</b>	<b>&lt; 0.001</b>
	Active	<b>93.2 (72.7, 100)</b>	<b>90.3 (72.4, 100)</b>	<b>&lt; 0.001</b>
	Passive	79.4 (70.2, 92.5)	77.7 (67.9, 90.7)	0.102
	Mixed	80.1 (70.5, 92.2)	79.9 (67.0, 91.1)	0.062
Off-road (% of route)	All	<b>18.3 (10.9, 31.6)</b>	<b>8.26 (2.35, 19.9)</b>	<b>&lt; 0.001</b>
	Active	<b>29.1 (18.2, 53.2)</b>	<b>10.8 (3.43, 23.6)</b>	<b>&lt; 0.001</b>
	Passive	<b>12.8 (8.98, 18.3)</b>	<b>5.74 (2.12, 18.8)</b>	<b>0.003</b>
	Mixed	<b>12.7 (7.65, 20.2)</b>	<b>5.90 (2.07, 20.2)</b>	<b>&lt; 0.001</b>
Residential roads (% of route)	All	<b>96.7 (66.3, 100)</b>	<b>100 (62.3, 100)</b>	<b>&lt; 0.001</b>
	Active	100 (77.6, 100)	100 (83.7, 100)	0.108
	Passive	69.4 (40.2, 100)	76.0 (42.0, 100)	0.659
	Mixed	<b>87.4 (65.3, 100)</b>	<b>85.4 (54.34, 100)</b>	<b>&lt; 0.001</b>

Data are presented as median (25th percentile, 75th percentile).

<sup>a</sup>p-value of difference between GPS and VERITAS routes (Wilcoxon signed-rank test).

Table 4–2 shows the best fit generalized linear mixed model for the predictors of difference in distance between the VERITAS and GPS routes. An active travel mode (as opposed to a passive travel mode) was associated with a 16.19% lower difference in distance from the GPS route ( $p = 0.05$ ). For every additional 1% of the GPS route that fell off-road, the difference in distance increased by 0.84% ( $p < 0.01$ ).

**Table 4–2.** Multilevel generalized linear mixed model of difference in distance between VERITAS and GPS routes.

	Coefficient	95% Confidence Interval		$p$
		Lower	Upper	
Intercept	22.8	10.1	35.3	< 0.001
Mode of travel <sup>a</sup>				
Active	<b>-16.2</b>	<b>-32.4</b>	<b>0.068</b>	<b>0.050</b>
Mixed	6.36	-8.91	21.6	0.414
VERITAS route distance	<b>-0.002</b>	<b>-0.003</b>	<b>-0.001</b>	<b>&lt; 0.001</b>
GPS route off-road (%)	<b>0.840</b>	<b>0.559</b>	<b>1.12</b>	<b>&lt; 0.001</b>

<sup>a</sup>Reference group = Passive travel mode.

Table 4–3 presents the route characteristics which predicted the degree of spatial agreement between the GPS and VERITAS routes. Routes travelled actively displayed 12.32% higher agreement relative to passive travel routes ( $p < 0.01$ ). Reporting that the route drawn in VERITAS was the only route they took was associated with 10.76% higher agreement ( $p < 0.01$ ). Every additional GPS trip segment reduced the agreement by 2.20% ( $p < 0.01$ ). The estimated marginal means and pairwise contrasts from the model in Table 4–3 were computed (i.e., adjusted for route distance, the number of GPS segments, and taking multiple routes to school). The adjusted percentage of spatial agreement was highest for active travel (75.52%; 95% CI = 70.86, 80.17). This was significantly greater than both passive (62.66%; 56.23, 69.10), and mixed (64.24%; 59.65, 68.83) travel modes (both pairwise contrasts  $p < 0.01$ ).

**Table 4–3.** Multilevel generalized linear mixed model of difference in percentage of spatial agreement between the VERITAS and GPS routes.

	Coefficient	95% Confidence Interval		p
		Lower	Upper	
Intercept	65.7	57.3	74.0	<0.001
Mode of travel <sup>a</sup>				
Active	<b>12.3</b>	<b>5.78</b>	<b>18.9</b>	<b>&lt;0.001</b>
Mixed	1.73	-4.85	8.31	0.605
Actual route distance	-0.000	-0.001	-0.000	0.337
No. of trip segments	<b>-2.20</b>	<b>-3.60</b>	<b>-0.819</b>	<b>0.002</b>
Take only one route <sup>b</sup>	<b>10.8</b>	<b>3.20</b>	<b>18.3</b>	<b>0.005</b>

<sup>a</sup>Reference group = Passive travel.

<sup>b</sup>Reference group = Take multiple routes to school (reported during VERITAS survey).

## Discussion

This study compared GPS-assessed routes to school with a route participants drew using an online mapping survey. To our knowledge, this is the first study which examines the comparability of GPS-assessed routes with those drawn using an interactive online map. Our results demonstrate that GPS-assessed routes were longer than the routes participants drew, and the level of spatial agreement between these routes varied by travel mode and other route characteristics. We will discuss the potential reasons for these findings, before addressing the practical considerations of both route assessment techniques.

The accrual of small positional errors during GPS assessment possibly contributed to longer GPS route distances, which were more pronounced for mixed and passive travel modes as these routes were generally longer. This is somewhat reinforced by the proportion of each route that fell off-road: 18.3% of the GPS routes fell off-road, which is more than double that of the VERITAS routes (7.1%). These figures are much higher than previously reported,<sup>236</sup> and may be explained by the lower GPS receiver sampling frequency utilised in the present study (15 versus 10 seconds), our use of multimodal trips, or differences in road and path network data (i.e., lack of pedestrian paths in our road dataset).

Participants appeared to intuitively follow street centrelines when drawing routes in VERITAS, meaning there was less chance of the VERITAS routes falling off-road, but this may have caused additional distance to be ignored (such as when crossing roads). Similarly, GPS trips with a higher number of segments (and therefore a higher number of

travel mode transitions) reduced the agreement between routes. It is likely that more distance was accumulated by the GPS receiver at travel mode transition points, such as public transit stations or parking lots, that was not captured when the VERITAS route was drawn.

Routes travelled actively reduced the difference in distance between the GPS and VERITAS routes by 16.2%, and improved the spatial agreement by 12.3% relative to passive travel modes. When people travel actively, they engage with their environment with a higher degree of intimacy, thus increasing their familiarity with local surroundings. It is possible that experiential knowledge gained from travelling actively translates into improved recognition of map features, such as buildings or groups of trees, which makes it easier to plot routes with a higher level of accuracy.<sup>256</sup> It was apparent that plotting long routes with a high degree of precision could become tedious, as a small number of participants who lived far away from school (i.e., 10+ km) tended to ‘cut corners’ when plotting their route by reducing the zoom level on the map. This was most evident on highways where subtle road curvatures are depicted as straighter lines when the map is zoomed out.

It is of particular interest that 40.7% of participants did not use the same travel mode across all school trips, and 29.9% reported taking multiple routes to school. Unsurprisingly, reporting taking only one school route was associated with 10.8% higher spatial agreement. In physical activity studies, it has been common to assess ‘usual’ travel mode and use a single school route to assess travel patterns and the relationship between mode choice and various environmental features.<sup>232-234,237,257,258</sup> Our results demonstrate this likely trivialises the complex nature of travel behaviours; in fact, participants who have a mixture of active and passive travel days are particularly important, because it means they live at a distance where active travel is possible, but they only travel actively on occasion. A person’s decision to use a different travel mode or take a different route to school can be dictated by many factors (e.g., weather, intermediary stops, availability of a parental car or travel companions), and identifying and understanding these will help to clarify the intricacies of travel decisions.

## **Practical considerations**

Online mapping has both advantages and disadvantages over GPS-based route assessment. Online mapping simplifies data processing because the raw data are already in the form of individual routes, and they do not need to be extracted from a larger dataset; a time consuming and error-prone process even with the correct tools and expertise. Manual trip extraction from GPS data has limited participant retention in a previous study;<sup>238</sup> however, our automated approach also resulted in the loss of some school trips (see limitations below). While our trip recognition algorithms could be improved, this does demonstrate the difficulties of extracting precise route information from GPS data. Participant burden may also be reduced, as spending a short period drawing a route is much less arduous than wearing and charging a GPS receiver, and has a lower chance of data loss.

Nonetheless, an inherent limitation of online mapping is the lack of temporal information. This means it is not possible to objectively assess travel time, or match other timestamped data (such as accelerometer or heart rate data) to extract physical activity information along the route. Besides route assessment, GPS receivers allow researchers to evaluate health behaviours across time and place, and answer more specific research questions, such as how time spent in greenspace affects health.<sup>259</sup> Although these data offer detailed information about where and when, they provide less information about why particular behaviours occur.<sup>204</sup> Conversely, interactive mapping protocols help to stimulate recall, and encourage participants to provide detailed personal-level information about their interaction with their environment, such as their likes, dislikes, perceptions and preferences.<sup>192</sup> This type of ‘geocoded knowledge’ can be useful for urban planners when creating safe and user-friendly environments.<sup>220</sup>

Considering that online mapping techniques are designed for people who may not be familiar with web-based mapping services, the design of the software is important to aid ease of use and information transfer. While VERITAS-BEANZ was developed for use in adolescents, previous online mapping surveys have been designed specifically for younger children.<sup>218</sup> During the BEANZ study, we noted the ability to control zoom and overlay satellite imagery assisted participants with identifying locations as they were able to recognise familiar landmarks.<sup>245</sup> The ease of editing routes is important to save participants time and maximise the accuracy of reported information, especially for those who may not be accustomed to reading maps. We found the presence of the undo button useful in cases where participants accidentally overshot a road or path they intended to turn

down, as they could easily remove and replace the last point in the path. One feature not implemented in the current version of VERITAS is the ‘snap to roads’ feature present in the Google Maps API. As alluded to previously, there is more room for error when longer routes are drawn, but the snap to roads feature could potentially overcome this issue, especially if bicycle and pedestrian path data are available. Although, the ability to toggle this feature is necessary as not all travel routes follow roads.

## **Limitations**

Firstly, a total of 595 trips to school were extracted using our automated approach, much less than the possible 955 school trips from 191 participants over five school days. There are several reasons why home-to-school trips did not get recognised. If the trip did not start within 50 m of the home (due to GPS problems or otherwise), or the trip contained intermediary stops longer than 10 min (the threshold set for combining trip segments), the trip would have been omitted. Compliance with monitor-wear protocols is a known issue in field-based research<sup>260</sup> and our wear time results demonstrate that some participants did not wear the GPS receiver for all days in the assessment period.

Secondly, our classification of mixed travel did not consider the number of ‘active’ and ‘passive’ segments, and the length and duration of these segments. It is possible that the majority of a trip was passive, but was classed as mixed travel (e.g., getting dropped off 100 m from the school boundary after a 5-km vehicle trip) or vice versa, and may be a reason our models showed non-significant differences between mixed and passive travel modes. The classification of multimodal trips is an area which has received relatively little attention. Perhaps a stricter set of criteria are needed to determine if a trip should be classified as multimodal. Finally, GPS is sometimes referred to as the gold standard for route assessment, but its accuracy is still subject to environmental conditions<sup>100,246</sup>. These positional errors, however slight, may have affected the agreement between routes.

## **Conclusion**

This study evaluated the comparability of two different techniques for assessing school travel routes in adolescents. We demonstrated that school routes assessed via portable GPS receiver were longer than routes drawn within an online mapping survey, and the spatial agreement between these routes was significantly higher when active travel modes were utilised. While cumulative GPS positional error may have contributed to some of these discrepancies (particularly for longer routes), we found that travel mode transitions (such as during public transit) and taking multiple routes to school also explained some of the variation between routes.

Although GPS receivers provide valuable information about time and place, these data cannot be used to determine why certain behaviours occur; information that interactive online mapping surveys are able to capture. If researchers are interested in the full spatiotemporal patterns of travel behaviours, then the use of GPS receivers is warranted. However, online mapping surveys may be more useful for understanding the intricate reasons behind travel decisions, or exploring travel in a localised area. Researchers will have to weigh up the advantages and disadvantages of each approach, and decide if the data obtainable are suitable for their study design and sufficient to answer their research questions.

## **Chapter 5 - Adolescents who engage in active school transport are also more active in other contexts: a space-time investigation**

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### **Preface**

The previous chapter revealed the average length of active school trips was approximately 1.5 km, but the average length of all school trips was close to 3 km, with many significantly longer. This suggests that walking to school may not be a practical option for many. Chapter 5 was conceived by recognising that most research on adolescents' physical activity and travel behaviours have focused almost exclusively on the school trip. However, it is estimated New Zealand adolescents spend more time per week (collectively) travelling to destinations other than school, so non-school destinations may provide important physical activity opportunities. Through the integration of GPS receivers, accelerometers, and innovative data processing methodology, this chapter examines the school trip's physical activity contribution, and how school travel behaviours are representative of wider mobility patterns. The paper from this chapter is currently published in the January 2017 issue of *Health & Place* (Appendix D).

## **Abstract**

**Background:** Although active school travel (AST) is important for increasing moderate-to-vigorous physical activity (MVPA), it is unclear how AST is related to wider physical activity patterns and non-school travel behaviours. This study investigated how school travel is related to physical activity and travel behaviours across four time- and space-classified domains: home, school, transport, and leisure.

**Methods:** A total of 196 adolescents wore a Global Positioning System (GPS) receiver and an accelerometer for 7-days. Trips to and from school were identified and their travel mode estimated. All GPS and accelerometer data were classified into one of four physical activity domains. Generalised linear mixed models were used to compare domain-specific physical activity and non-school trips between active and passive school travellers.

**Results:** Active travellers accumulated 12.8 and 14.4 more min of MVPA on weekdays and weekend days, respectively. They also spent 14.9 min less time in vehicular travel during non-school trips, and accrued an additional 9.27 min of MVPA while walking on weekend days. However, individuals who use passive forms of travel to and from school still achieved most of their MVPA in the transport domain.

**Conclusions:** AST is related to out-of-school physical activity and transportation, but physical activity in the transport domain is also important for those who do not engage in AST. As such, future studies should consider overall mobility and destinations other than school when assessing travel patterns in relation to the built environment.

## Introduction

Being physically active during adolescence is important for physical, social, and emotional wellbeing,<sup>4</sup> and the development of physical activity behaviours which may persist into adulthood.<sup>261</sup> Walking or cycling for transportation has been recognised as an effective way for young people to engage in physical activity, yet the mode share of these ‘active travel’ trips has been steadily declining over the last few decades, including in New Zealand.<sup>229,262</sup> Consequently, more attention is being placed on understanding the environments and policies that support physical activity and active transportation across the lifespan.<sup>19</sup>

The majority of studies investigating how young people’s travel behaviours relate to physical activity and the environment have focused exclusively on school travel.<sup>28,29</sup> The school trip’s prominence is due to its commonality among all young people, the frequency of the school commute (10 times per week), and hence the cumulative physical activity potential of these trips. Although a significant contributor to physical activity on weekdays,<sup>28</sup> school travel may not truly represent the totality of an individual’s activity patterns and travel behaviours, especially for those who live too far from school for walking or cycling to be a feasible travel mode choice.<sup>263</sup> The priority placed on the school trip has likely contributed to the conflicting evidence surrounding school travel and weight-related health markers, as indicated by recent reviews of over 70 studies.<sup>28,226</sup>

Adolescents can be physically active within numerous other contexts, particularly on non-school days. However, defining exposure to contextual or environmental influences is challenging, as movement through the environment occurs across space and time, varies from person to person, and is highly individualised.<sup>185</sup> Defining contexts in which people spend their time is shifting from static conceptualisations of place, which ignore the important role of time (i.e., the neighbourhood), to more fluid and dynamic constructs that take both time and space into account.<sup>171,264</sup>

Global Positioning System (GPS) technology and custom-designed data processing software have been used to classify young people’s activity behaviours into various domains which can be defined both temporally and/or spatially.<sup>26,103</sup> The identification of these ‘space-time’ domains not only makes it easier to conceptualise activity patterns across time and space, but also how these domains are related to each other, and how these patterns vary among different groups of people. For example, travel behaviours may be related to physical activity accrued during leisure time, but these trends may differ

between individuals living in urban and rural areas. Establishing where these disparities lie is important as they will likely aid the development of context- and population-specific behavioural, environmental, and policy initiatives.

Earlier studies investigating how school travel decisions are related to overall physical activity behaviours have focused purely on temporally-classified domains, such as before, during, and after school, and in the weekend.<sup>265-267</sup> Although these studies demonstrated that active school travel was positively associated with out-of-school physical activity, they were unable to determine where, how, and for how long these activities occurred. Whether school travel behaviours are related to context-specific physical activity, or if these behaviours are representative of overall transportation practices, is not well understood. By utilising a combination of accelerometer-based activity monitors, GPS receivers, and innovative data processing methodology, the aims of this study were (1) to determine how objectively-assessed school travel mode is related to physical activity accumulated within various space-time domains, and (2) to determine how school travel behaviours correspond with non-school trips.

## **Methods**

### **Participants**

A total of 196 adolescents (12–18 years old) were recruited from seven secondary schools in Auckland and Wellington, located on New Zealand's North Island. Participants were a subsample of those recruited for the Built Environment and Adolescent New Zealanders (BEANZ) study. The BEANZ recruitment methodology has previously been described in detail.<sup>34</sup> In brief, socioeconomic status (SES) and meshblock-level (smallest census tract units available in New Zealand) walkability indices were calculated for all participants at the selected schools based on their residential addresses (obtained from the school prior to the consent process). These scores were organised into tertiles, and the highest and lowest tertiles were retained to create four strata: (1) high walkability, high SES; (2) high walkability, low SES; (3) low walkability, high SES and (4) low walkability, low SES. All participants residing in one of these strata were invited to participate via invitations distributed through each school. This strategy was chosen to maximise heterogeneity in the built environment and SES variables. Written informed consent and assent was obtained from parents and adolescents (respectively) prior to participation. From this pool

of consenting students, a stratified sub-sample of approximately 30 students per school was selected to balance participants across the four strata. Participants in this subsample were assessed concurrently with the main BEANZ sample. Ethical approval was granted by the Auckland University of Technology Ethics Committee.

## **Instruments**

### ***GPS receiver***

GPS receivers can predict their geographical location by processing signals received from satellites orbiting the earth. By logging this information over a period of time, movement across space can be recorded. The QStarz BT-Q1000XT is a commercially available GPS receiver that utilises the MTK II chipset. This device is known to have high accuracy while stationary<sup>100</sup> and while moving in free-living conditions.<sup>246</sup> Using QTravel software (v1.46, Taipei, Taiwan) each device was initialised to log data every 15 s to maximise the frequency of data points whilst reserving memory capacity for a one-week period. Additional satellite information such as signal-to-noise ratio was also recorded to assist with indoor/outdoor detection and thus trip identification (see data reduction below).

### ***Accelerometer***

The activity monitor used in this study was the Actigraph GT3X+ (Actigraph, Pensacola, FL). This activity monitor contains a capacitive accelerometer capable of collecting raw acceleration information at a sampling frequency up to 100 Hz. These are small (46 mm x 33 mm x 15 mm) lightweight (19 g) devices, and are widely used due to their ability to assess free-living physical activity intensity over an extended period with a low degree of participant burden.<sup>268</sup> Each device was initialised to log raw data at 30 Hz using Actilife v6 (Actigraph, Pensacola, FL). The system time on the computer used to initialise all devices was synchronised with Coordinated Universal Time (UTC) so the internal clock of each accelerometer was aligned with each GPS receiver to allow the precise matching of data points during processing.

## **Procedure**

Participant details were obtained from each child and parent during the consent process. Each school provided weekly timetables from which the start and end times for each

school day were extracted. During school time, each participant was fitted with an accelerometer and GPS receiver using an elastic waist belt. Only those in the subsample wore a GPS receiver, while all participants in the BEANZ study received an accelerometer. The accelerometer was positioned over the right hip, and the GPS receiver was placed alongside in a small pouch. Each participant was taught how to wear the devices and how to charge the GPS receiver before they went to sleep at night. Participants were told that the GPS receiver should remain on at all times, but were provided with instructions how turn the device off and on again if necessary. The equipment was collected from the school eight days later, at which point each participant received a \$20 shopping mall voucher thanking them for participating. Upon retrieval, accelerometer data were downloaded and aggregated to a 15-s epoch (using Actilife v6) to match the sampling frequency of the GPS receivers. All GPS and accelerometer data were converted to comma-separated values (csv) format in preparation for processing.

## **Data reduction**

### ***PALMS***

All GPS and accelerometer data were uploaded to the Personal Activity Location Measurement System (PALMS; <https://ucsd-palms-project.wikispaces.com>). PALMS is a web-based tool designed to clean, merge and process multiple time-stamped data streams. PALMS was used to remove spurious points based on a set of filter criteria: points with a speed above  $130 \text{ km}\cdot\text{h}^{-1}$ , points with a change in elevation greater than 1000 m, or points with less than 10 m of movement over 3 sequential fixes were removed. After the accelerometer and GPS data were merged, PALMS identified individual trips based on sequential GPS points accumulated over a period of at least 2 min that spanned at least 100 m. Trip pauses were identified based on clusters of sequential points at a single location. The end of a trip was signified by a pause greater than 3 min or a loss-of-signal. Each GPS point was categorised as indoors or outdoors based on the signal-to-noise ratio (SNR): all points with a sum SNR of less than 225 were considered indoor points, and these were removed from the beginning and end of all trips. Each trip was assigned a mode of travel based on speed; minimum speeds were  $35 \text{ km}\cdot\text{h}^{-1}$  for vehicle,  $10 \text{ km}\cdot\text{h}^{-1}$  for bicycle, and  $1 \text{ km}\cdot\text{h}^{-1}$  for walking, where the 90th percentile of speeds along the trip were considered. These PALMS trip detection and mode of travel parameters have shown reasonably high accuracy ( $> 75\%$ ) when compared to camera image data over a four day period.<sup>248</sup> All physical activity data were classified into sedentary, light, moderate, and

vigorous intensity categories using the thresholds provided by Evenson *et al.*<sup>93</sup> and non-wear time was defined as 60 min of consecutive zero counts. A day was considered valid if it had at least 8 hours of wear time (7 hours on weekend days) after non-wear time removal.

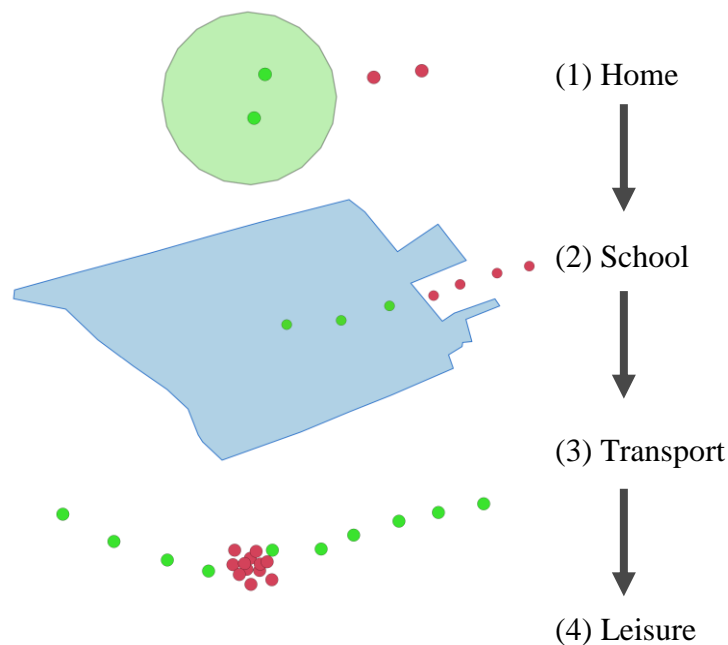
## ***PostgreSQL***

### *School trip extraction*

Participant's addresses were geocoded using ArcGIS 10.3 (ESRI, Redlands, CA, USA). A 50 m Euclidean buffer was applied to each home point, and each schoolyard boundary was digitised within ArcGIS using high resolution digital imagery. Both of these layers, along with the PALMS output, were input into a custom-designed PostgreSQL (<http://www.postgresql.org>) geodatabase using the PostGIS extension (<http://postgis.net>). PostgreSQL is an open-source, object-relational database system used to easily store and retrieve data. The PostGIS extension adds support for geographic objects, and provides spatial operators which permit the use of spatial queries. PALMS is currently unable to identify multimodal trips because each change in travel mode signifies the end of the current trip, and the beginning of the next. Accordingly, a trip was classified as a multimodal trip segment if both a spatial and temporal criterion were met: (1) the start point of the trip was within 200 m of the end point of the previous trip, and (2) the start time of the trip was within 10 min of the previous trip's end time. Segments that were identified as being part of the same trip were then merged, along with their attributes, into a new trip trajectory. The length, duration, speed, minutes of MVPA, minutes of sedentary time, average counts-per-minute (CPM), and mode of travel were preserved per trip. As hip-mounted accelerometers cannot accurately assess physical activity intensity whilst cycling, the CPM and MVPA accumulated during cycling trips were corrected in line with methods developed in a sample of Danish adolescents.<sup>96</sup> The adjustment was based on an underestimation factor of 9,314 counts and 2.7 min of MVPA for every kilometre of the cycle journey. All trips that were purely walking and cycling trips, whether single mode or multimodal were defined as active travel trips. For example, if a trip consisted of both vehicle and walking segments, it was considered a passive travel trip. All trips that started inside the home buffer and ended inside the schoolyard polygon (or vice versa) on weekdays were classified as school trips.

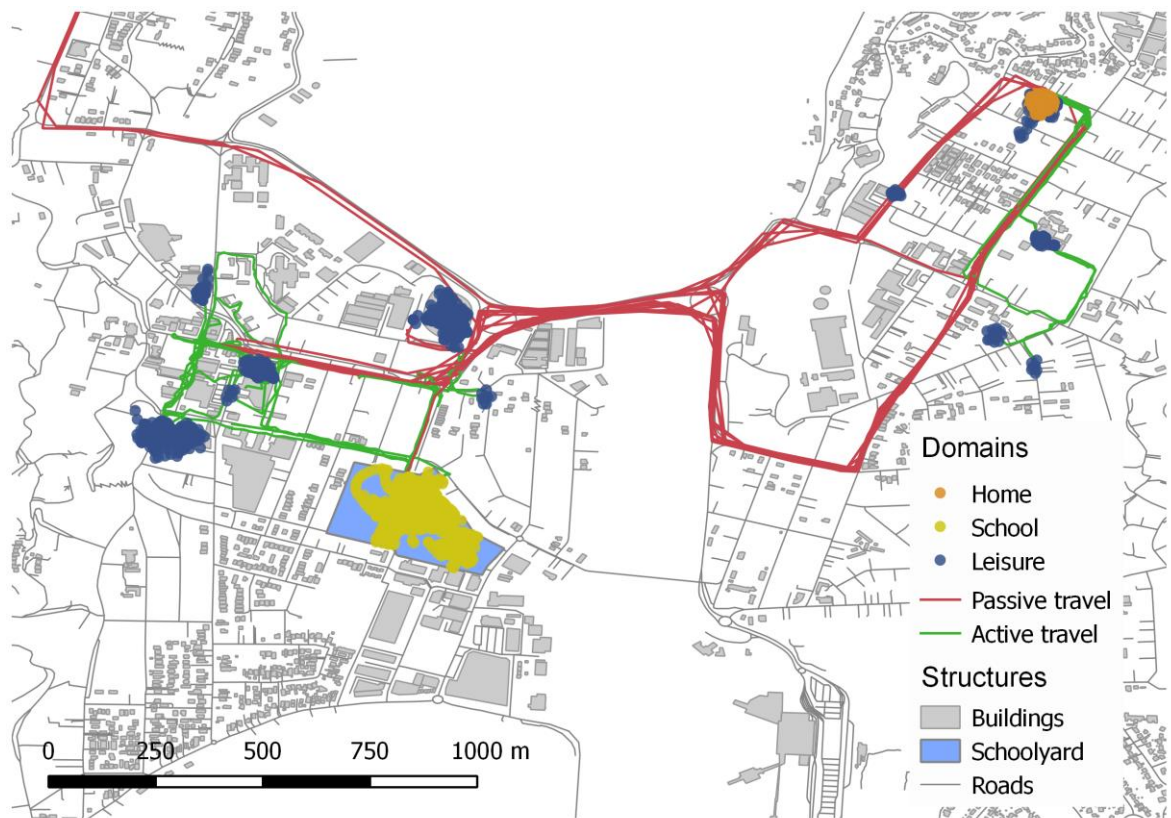
### *Domain classification*

All merged PALMS output points were classified as belonging to one of four mutually exclusive space-time domains: home, school, transport, or leisure. Each point was passed through a simple decision tree to determine which of the four domains it should be assigned: (1) all points within the 50 m buffer of the participant's home address were assigned to the home domain; (2) all points that fell within the schoolyard polygon during school hours (based on individual school timetables) were assigned to the school domain; (3) all points belonging to PALMS-identified trips were assigned to the transport domain; and (4) all remaining points not assigned to home, school or transport were assigned to the leisure domain (see Figure 5–1). The transport domain can be interpreted as the travel between places, while the leisure domain can be interpreted as places where adolescents spent time other than home or school (see Figure 5–2). The following variables were generated per person, per day, for each of the domains: minutes of instrument wear time, MVPA, and sedentary time, and average CPM.



**Figure 5–1.** Domain classification of GPS points.

The green and blue polygons represent the home buffer and schoolyard boundary, respectively. Green points are valid while red points are passed to the next step in the decision tree. Any points unclassified after step three are assigned to the leisure domain.



**Figure 5–2.** Domain-classified PALMS output data from a single participant.

Points in the transport domain have been converted to lines and coloured based on mode of travel. This example demonstrates an adolescent who does not engage in AST, but travels actively to other destinations.

## Statistical Analysis

Descriptive statistics for all school trip parameters were calculated and presented as the median and interquartile range (IQR) as the data were not normally distributed. To investigate how school travel was related to domain-specific physical activity and overall transportation behaviours, both day-level and person-level analyses were undertaken using a series of multilevel generalised linear mixed models (GLMMs) to account for the hierarchical data structure and the nesting of days within individuals, within schools.<sup>254</sup>

In the first instance, to test the relation of active school travel (AST) and domain-specific physical activity, each day was grouped into one of three categories depending if there were none, one, or two AST trips occurring on that day. Minutes of instrument wear time as well as physical activity parameters (CPM, MVPA, sedentary time) recorded across the day and in each of the four domains were compared between these three groups. This analysis occurred at the day-level (i.e., days formed the repeated measure) and therefore all valid days (i.e., at least 8 hours wear time) were included. The output of this analysis

can be interpreted as the differences in domain-specific physical activity contrasted by AST frequency on any given weekday, irrespective of person.

Secondly, several person-level analyses were undertaken, where people were organised into two groups based on their AST frequency across the five measured school days. Individuals were classed as active travellers if at least half of their recorded school trips (both to and from school) were active travel trips, and if not, they were classed as passive travellers. Similar to the above analyses, wear time and activity parameters across each of the four domains and the full day were compared between these two groups, for both weekdays and weekend days.

Finally, a person-level approach was taken to test if school travel behaviours were related to overall transportation practices. First, all school trips were removed from the trips dataset, and trip parameters (length, duration, CPM, MVPA) for the remaining trips were aggregated per mode of travel (walking, cycling, vehicle), per person. These trip parameters were then compared between the active and passive traveller groups, for both weekdays and weekend days. At least three valid weekdays were necessary for inclusion in all person-level analyses, and at least one weekend day for weekend comparisons. Adolescent AST and physical activity has been shown to vary by age and sex.<sup>269,270</sup> Consequently, all models were adjusted for participant age and sex, and models with MVPA or sedentary time as the dependant variable were further adjusted for domain-specific (or total day) wear time, as more wear time equates to an increased opportunity to engage in MVPA or sedentary practices. Statistical significance was set at  $p < 0.05$ , and all analyses were conducted in IBM SPSS Statistics v23 (IBM Cooperation, USA).

## **Results**

Table 5–1 presents participant characteristics and wear time descriptives. In total, 186 participants met the wear time criteria and were included in analysis. Approximately 6.1 million cleaned and matched GPS and accelerometer data points were classified into the four space-time domains. From these points, 12,083 individual trips were identified, 1,172 of which were school trips. On average, the MVPA accumulated during the trips to and from school accounted for 21.5% and 17.9% of total weekday MVPA, respectively. Table 5–2 shows the physical activity and route characteristics of these school trips dissected by travel mode. Multimodal walk and vehicle trips were the most common

(48.0%), followed by single-mode walking trips (33.5%) and vehicle trips (12.0%). Purely active travel trips (i.e., walk, bicycle, or walk and bicycle trips) had an average of 12.1 min of MVPA compared to 4.3 min for modes that contained passive travel (i.e., vehicle, or walk and vehicle trips).

**Table 5–1.** Participant demographic and compliance descriptives.

	Male (n = 110)	Female (n = 76)	All (n = 186)
Age (years)	14.7 ± 2.38	14.8 ± 2.09	14.7 ± 2.26
BMI (kg·m <sup>-2</sup> )	21.5 ± 4.86	22.3 ± 3.76	21.8 ± 4.46
Days with any wear time	5.41 ± 1.64	5.60 ± 1.75	5.49 ± 1.68
Days with 8+ hours wear time	4.96 ± 1.75	5.05 ± 1.98	5.00 ± 1.84
Wear time on valid days (hours)	12.2 ± 2.70	12.4 ± 2.85	12.3 ± 2.76
Active school travellers (%) <sup>a</sup>	34.2	28.6	31.9

Data presented as mean ± SD.

BMI = Body Mass Index.

<sup>a</sup>Classified as ≥ 50% of all school trips travelled actively.

**Table 5–2.** School trip descriptives dissected by travel mode.

	MULTIMODAL TRIPS (n = 607)				SINGLE MODE TRIPS (n = 565)		
	Walk & Vehicle (n = 562)		Walk & Bicycle (n = 45)				
	Walk	Vehicle	Walk	Bicycle	Walk (n = 393)	Vehicle (n = 141)	Bicycle (n = 31)
Duration (min)	9.50 (5.25, 16.0)	17.0 (8.25, 27.1)	4.75 (3.13, 9.38)	15.3 (10.4, 21.3)	21.0 (14.0, 29.4)	10.3 (7.00, 17.5)	12.0 (9.75, 16.3)
Length (km)	0.54 (0.30, 0.98)	4.92 (2.55, 12.1)	0.20 (0.14, 0.47)	2.62 (1.82, 3.31)	1.42 (0.98, 2.00)	3.43 (2.39, 7.47)	2.36 (1.85, 2.95)
CPM	2940 (1900, 4460)	479 (171, 1290)	2150 (1410, 3200)	2150 (1370, 3630)	3180 (2400, 4040)	879 (370, 1510)	2840 (1710, 3590)
MVPA (min)	4.50 (2.50, 8.75)	1.75 (0.50, 4.25)	2.00 (1.25, 3.25)	10.6 (8.37, 13.6)	13.3 (8.25, 20.0)	2.25 (0.75, 3.50)	10.4 (8.38, 12.0)
Speed (km·h <sup>-1</sup> )	4.41 (3.43, 7.21)	29.3 (21.1, 43.4)	3.16 (2.42, 5.82)	12.3 (10.1, 16.0)	4.42 (3.98, 5.20)	25.0 (18.2, 29.9)	11.5 (9.69, 14.8)

Data presented as median (IQR).

CPM = Counts per minute.

MVPA = Moderate-to-vigorous physical activity.

Table 5–3 presents overall and domain-classified wear time and physical activity contrasted by daily AST frequency (day-level analysis). The majority of school days contained no active travel (61.2%), while 20% of days contained active trips both ways (i.e., both to and from school). Of the days with one active school trip, 69.7% contained a trip to school. Compared to a day with no AST, if an adolescent travelled actively one-way or both ways, they accumulated 11 min (+22.9%) and 15.1 min more MVPA (+31.3%), respectively. Likewise, days with one or two AST trips had 10.3% and 15.0% higher overall daily average CPM, respectively. When stratified by domain, noticeable differences were seen during transport, with adolescents accumulating approximately 11 min more MVPA on days containing AST. On these AST days, adolescents spent 14 min less time in the transport domain, and spent approximately 10 min less time sedentary while travelling. Slightly more MVPA and less sedentary time were seen in the leisure domain on AST days. The only significant pairwise contrasts between travelling actively one-way or both ways were wear time in the school domain (26.7 min;  $p = 0.049$ ) and average CPM during transport (403 CPM;  $p < 0.001$ ). An interesting observation is on days with no AST: 18.7 min of MVPA was still accumulated in the transport domain.

**Table 5–3.** Estimated marginal means and pairwise contrasts of AST frequency across different domains on weekdays (day-level analysis).

Domain		No active travel (n = 496 days)	Active travel one-way (n = 152 days)	One-way – none Difference (%)	Padja	Active travel both ways (n = 162 days)	Both ways – none Difference (%)	Padja
Day	Wear time (min)	696 (675, 718)	693 (686, 727)	-3.15 (-0.45%)	0.867	722 (687, 757)	25.9 (3.71%)	0.561
	CPM	<b>1020 (963, 1080)</b>	<b>1120 (1050, 1200)</b>	<b>105 (10.3%)</b>	<b>0.008</b>	<b>1170 (1100, 1250)</b>	<b>153 (15.0%)</b>	<b>&lt;0.001</b>
	MVPA (min)	<b>48.3 (44.1, 52.6)</b>	<b>59.4 (53.6, 65.1)</b>	<b>11.0 (22.9%)</b>	<b>&lt;0.001</b>	<b>63.4 (57.4, 69.5)</b>	<b>15.1 (31.3%)</b>	<b>&lt;0.001</b>
	Sedentary (min)	491 (482, 500)	476 (465, 488)	-14.6 (-2.97%)	0.055	478 (466, 491)	-12.6 (-2.56%)	0.117
Home	Wear time (min)	272 (249, 295)	241 (209, 273)	-31.3 (-11.5%)	0.205	267 (234, 301)	-5.20 (-1.91%)	0.777
	CPM	738 (688, 789)	792 (723, 861)	53.4 (7.23%)	0.292	<b>848 (775, 922)</b>	<b>110 (14.9%)</b>	<b>0.018</b>
	MVPA (min)	7.59 (6.59, 8.60)	7.51 (6.01, 9.02)	-0.08 (-1.05%)	1.000	8.24 (6.67, 9.80)	0.65 (8.56%)	1.000
	Sedentary (min)	196 (192, 200)	195 (189, 201)	-0.91 (-0.47%)	0.907	199 (193, 204)	2.75 (1.40%)	0.907
School	Wear time (min)	<b>247 (233, 261)</b>	<b>295 (274, 317)</b>	<b>48.5 (19.6%)</b>	<b>&lt;0.001</b>	<b>322 (300, 344)</b>	<b>75.2 (30.5%)</b>	<b>&lt;0.001</b>
	CPM	<b>731 (685, 777)</b>	<b>902 (829, 974)</b>	<b>171 (23.3%)</b>	<b>&lt;0.001</b>	<b>896 (821, 970)</b>	<b>165 (22.5%)</b>	<b>&lt;0.001</b>
	MVPA (min)	14.9 (13.5, 16.3)	14.6 (12.5, 16.7)	-0.30 (-2.01%)	1.000	14.7 (12.5, 17.0)	-0.18 (-1.21%)	1.000
	Sedentary (min)	188 (184, 193)	192 (182, 195)	3.06 (1.62%)	1.000	189 (182, 195)	0.34 (0.18%)	1.000
Transport	Wear time (min)	<b>71.0 (65.6, 76.5)</b>	<b>56.7 (48.9, 64.5)</b>	<b>-14.3 (-20.1%)</b>	<b>0.003</b>	<b>56.5 (48.4, 64.6)</b>	<b>-14.5 (-20.4%)</b>	<b>0.003</b>
	CPM	<b>1710 (1570, 1850)</b>	<b>2340 (2160, 2520)</b>	<b>631 (30.9%)</b>	<b>&lt;0.001</b>	<b>2740 (2550, 2940)</b>	<b>1030 (60.5%)</b>	<b>&lt;0.001</b>
	MVPA (min)	<b>18.7 (16.5, 20.9)</b>	<b>28.6 (25.7, 31.6)</b>	<b>9.90 (52.8%)</b>	<b>&lt;0.001</b>	<b>31.7 (28.6, 34.8)</b>	<b>12.9 (69.0%)</b>	<b>&lt;0.001</b>
	Sedentary (min)	<b>37.4 (35.4, 39.3)</b>	<b>27.7 (24.8, 30.6)</b>	<b>-9.70 (-26.0%)</b>	<b>&lt;0.001</b>	<b>26.2 (23.2, 29.1)</b>	<b>-11.2 (-30.0%)</b>	<b>&lt;0.001</b>
Leisure	Wear time (min)	<b>113 (101, 125)</b>	<b>87.0 (69.7, 104)</b>	<b>-25.8 (-22.9%)</b>	<b>0.012</b>	<b>67.8 (49.8, 85.8)</b>	<b>-45.1 (-40.0%)</b>	<b>&lt;0.001</b>
	CPM	876 (798, 954)	925 (809, 1040)	49.1 (5.61%)	1.000	925 (805, 1050)	48.8 (5.57%)	1.000
	MVPA (min)	<b>6.72 (5.33, 8.10)</b>	<b>9.46 (7.36, 11.6)</b>	<b>2.74 (40.8%)</b>	<b>0.039</b>	<b>9.79 (7.61, 12.0)</b>	<b>3.07 (45.7%)</b>	<b>0.039</b>
	Sedentary (min)	<b>70.0 (67.4, 72.5)</b>	<b>63.5 (59.6, 67.7)</b>	<b>-6.45 (-9.22%)</b>	<b>0.016</b>	<b>63.6 (59.4, 68.0)</b>	<b>-6.43 (-9.19%)</b>	<b>0.016</b>

Data are presented as mean (95% CI) unless otherwise stated.

CPM = Counts per minute.

MVPA = Moderate-to-vigorous physical activity.

<sup>a</sup>Adjusted using sequential Bonferroni correction.

Results obtained from a generalized linear mixed model using a normal distribution and an identity link function. Fixed effects = Age, Sex; Random effects = City\*School\*Person; Repeated measure = Days. MVPA and Sedentary time are also adjusted for domain specific wear time (more wear time equates to an increased opportunity to be sedentary or active).

Considering that adolescents may not use the same travel mode each day, and may even take multiple travel routes to and from school, person-level analyses are important to determine if these day-level trends persist across a typical week, and to examine the effects of AST on actual individuals. The mean proportion of school trips travelled actively was 74.0% in the active travellers group, and 4.8% in the passive travellers group. Table 5–4 shows overall and domain-classified wear time and physical activity contrasted by AST group, for both weekdays and weekend days. Active travellers accumulated 12.8 min more MVPA on weekdays (+26.3%), and 14.4 more min on weekend days (+41.2%), compared to passive travellers. Active travellers accumulated an additional 11.7 min of MVPA (+62.0%) and 10.6 min less sedentary time (-29.3%) in the transport domain on weekdays, and these trends persisted during the weekend. Active travellers also had more MVPA and less sedentary time in the leisure domain, but only on weekdays. For active and passive travellers, the transport domain accounted for 49.7% and 38.7% of total MVPA on weekdays, respectively, while the school domain accounted for 25.7% and 29.7% of MVPA, respectively.

**Table 5–4.** Estimated marginal means and pairwise contrasts of PA across different domains, grouped by AST frequency (person-level analysis).

		WEEKDAYS				WEEKEND DAYS			
Domain		Passive Travellers (n = 126)	Active Travellers (n = 60)	Active – Passive Difference (%)	Padj <sup>a</sup>	Passive Travellers (n = 87)	Active Travellers (n = 45)	Active – Passive Difference (%)	Padj <sup>a</sup>
Day	Wear time (min)	692 (668, 715)	711 (677, 745)	19.0 (2.75%)	0.358	622 (579, 665)	670 (609, 731)	48.1 (7.72%)	0.204
	CPM	<b>1020 (962, 1090)</b>	<b>1150 (1060, 1240)</b>	<b>126 (12.3%)</b>	<b>0.023</b>	899 (808, 990)	1040 (910, 1170)	141 (15.7%)	0.079
	MVPA (min)	<b>48.8 (44.3, 53.2)</b>	<b>61.6 (55.1, 68.1)</b>	<b>12.8 (26.3%)</b>	<b>0.002</b>	<b>35.0 (27.7, 42.4)</b>	<b>49.5 (39.0, 59.9)</b>	<b>14.4 (41.2%)</b>	<b>0.027</b>
	Sedentary (min)	486 (476, 495)	477 (464, 490)	-8.70 (-1.79%)	0.288	441 (425, 456)	442 (420, 463)	0.91 (0.21%)	0.946
Home	Wear time (min)	259 (234, 284)	281 (245, 317)	22.5 (8.68%)	0.308	378 (321, 434)	416 (337, 496)	38.9 (10.3%)	0.429
	CPM	785 (717, 852)	822 (723, 921)	37.3 (4.75%)	0.537	719 (632, 806)	786 (663, 909)	66.7 (9.28%)	0.380
	MVPA (min)	7.61 (6.53, 8.70)	8.33 (6.74, 9.91)	0.71 (9.33%)	0.461	11.7 (8.84, 14.5)	13.5 (9.45, 17.5)	-1.79 (-15.4%)	0.471
	Sedentary (min)	194 (188, 198)	197 (191, 204)	3.3 (1.7%)	0.406	290 (279, 302)	294 (278, 311)	4.07 (1.40%)	0.690
School	Wear time (min)	<b>252 (238, 266)</b>	<b>285 (265, 305)</b>	<b>33.3 (13.2%)</b>	<b>0.007</b>				
	CPM	779 (732, 827)	817 (748, 886)	37.5 (4.81%)	0.375				
	MVPA (min)	14.5 (13.0, 15.9)	15.8 (13.6, 17.9)	1.33 (9.20%)	0.313				
	Sedentary (min)	188 (184, 193)	189 (182, 196)	0.44 (0.23%)	0.915				
Transport	Wear time (min)	<b>72.8 (66.6, 78.9)</b>	<b>53.9 (44.9, 62.9)</b>	<b>-18.9 (-26.0%)</b>	<b>0.001</b>	66.1 (53.5, 78.7)	70.8 (52.9, 88.7)	4.72 (7.14%)	0.669
	CPM	<b>1740 (1580, 1900)</b>	<b>2560 (2330, 2790)</b>	<b>817 (46.9%)</b>	<b>&lt;0.001</b>	1440 (1140, 1750)	1890 (1460, 2320)	448 (31.1%)	0.096
	MVPA (min)	<b>18.9 (16.4, 21.5)</b>	<b>30.6 (26.9, 34.4)</b>	<b>11.7 (62.0%)</b>	<b>&lt;0.001</b>	<b>15.4 (10.8, 20.0)</b>	<b>25.8 (19.3, 32.3)</b>	<b>10.4 (67.1%)</b>	<b>0.011</b>
	Sedentary (min)	<b>36.1 (33.9, 38.3)</b>	<b>25.5 (22.3, 28.8)</b>	<b>-10.6 (-29.3%)</b>	<b>&lt;0.001</b>	<b>37.4 (33.8, 41.1)</b>	<b>29.7 (24.5, 34.8)</b>	<b>-7.74 (-20.7%)</b>	<b>0.016</b>
Leisure	Wear time (min)	108 (95.2, 121)	90.3 (71.4, 109)	-17.9 (-16.5%)	0.124	179 (145, 213)	183 (135, 231)	4.48 (2.51%)	0.880
	CPM	871 (788, 954)	934 (814, 1055)	63.2 (7.26%)	0.393	709 (594, 825)	818 (655, 982)	109 (15.4%)	0.282
	MVPA (min)	<b>7.00 (5.54, 8.45)</b>	<b>9.74 (7.62, 11.9)</b>	<b>2.75 (39.3%)</b>	<b>0.035</b>	9.80 (6.61, 13.0)	14.0 (9.5, 18.5)	4.2 (42.5%)	0.137
	Sedentary (min)	<b>68.9 (66.3, 71.5)</b>	<b>59.2 (58.2, 66.8)</b>	<b>-5.92 (-8.59%)</b>	<b>0.012</b>	114 (107, 121)	117 (107, 127)	3.35 (2.95%)	0.588

Data are presented as mean (95% CI) unless otherwise stated.

Passive Travellers (< 50% of all school trips active); Active Travellers (>= 50% of all school trips active).

CPM = Counts per minute.

MVPA = Moderate-to-vigorous physical activity.

<sup>a</sup>Adjusted using sequential Bonferroni correction.

Results obtained from a generalized linear mixed model using a normal distribution and an identity link function. Fixed effects = Age, Sex; Random effects = City\*School\*Person. MVPA and Sedentary time are adjusted for domain specific wear time (more wear time equates to an increased opportunity to be sedentary or active).

Higher MVPA within the transport domain is indicative of more active travel, and for this to be present on weekend days, as seen in Table 5–4, suggests that adolescents who travel actively to school also travel actively to destinations other than school. Accordingly, Table 5–5 presents differences in non-school-trip parameters between AST groups, for both weekdays and weekend days. When school trips were removed, there was no difference between AST groups in the duration, length, or physical activity accumulated during walking or bicycling on weekdays. However, those who engaged in AST regularly spent 15 min less time in a vehicle on weekdays (-47.6%). On weekend days, there were no differences in the distance or time spent within any of the travel modes, although those who engaged in AST regularly walked with a higher overall intensity (+69.8%), and by doing so, accumulated an additional 9.27 min of MVPA during walking (+93.1%). Further investigation revealed the speed of these weekend walking trips was 0.87 km·h<sup>-1</sup> faster in the active travellers group compared to the passive travellers (2.80 km·h<sup>-1</sup>, 3.68 km·h<sup>-1</sup>,  $p = 0.009$ ).

**Table 5–5.** Estimated marginal means and pairwise contrasts of non-school trip parameters between AST groups (person-level analysis).

		WEEKDAYS				WEEKEND DAYS			
Mode of Travel		Passive Travellers (n = 126)	Active Travellers (n = 60)	Active – Passive Difference (%)	Padj <sup>a</sup>	Passive Travellers (n = 87)	Active Travellers (n = 45)	Active – Passive Difference (%)	Padj <sup>a</sup>
	Total trips	8.51 (7.95, 8.74)	7.92 (7.11, 8.74)	-0.59 (-6.93%)	0.240	6.53 (5.54, 7.51)	6.03 (4.63, 7.42)	-0.5 (-7.66%)	0.562
Vehicle	Length (km)	<b>18.0 (14.3, 21.7)</b>	<b>9.45 (4.06, 14.8)</b>	<b>-8.51 (-47.3%)</b>	<b>0.010</b>	30.1 (21.1, 39.1)	29.1 (16.3, 41.9)	-0.95 (-3.16%)	0.904
	Duration (min)	<b>31.3 (27.0 35.5)</b>	<b>16.4 (10.2, 22.6)</b>	<b>-14.9 (-47.6%)</b>	<b>&lt;0.001</b>	44.4 (35.0, 53.8)	41.9 (28.6, 55.3)	-2.42 (-5.45%)	0.768
	CPM	<b>469 (399, 539)</b>	<b>245 (142, 348)</b>	<b>-234 (-49.9%)</b>	<b>&lt;0.001</b>	298 (215, 382)	352 (233, 470)	53.4 (17.9%)	0.464
	MVPA (min)	<b>1.63 (1.31, 1.95)</b>	<b>0.53 (0.07, 1.00)</b>	<b>-1.1 (-67.5%)</b>	<b>&lt;0.001</b>	1.12 (0.41, 1.83)	1.81 (0.81, 2.81)	0.69 (61.6%)	0.266
Walk	Length (km)	3.38 (3.06, 3.70)	2.92 (2.45, 3.38)	-0.46 (-13.6%)	0.107	2.11 (1.57, 2.66)	2.70 (1.94, 3.47)	0.59 (28.0%)	0.214
	Duration (min)	69.0 (62.3, 75.7)	60.5 (50.8, 70.3)	-8.47 (-12.3%)	0.156	45.3 (34.8, 55.8)	51.2 (36.3, 66.1)	5.92 (13.1%)	0.520
	CPM	1670 (1510, 1820)	1650 (1420, 1880)	-17 (-1.02%)	0.902	<b>1170 (874, 1460)</b>	<b>1980 (1570, 2400)</b>	<b>816 (69.8%)</b>	<b>0.002</b>
	MVPA (min)	15.5 (13.5, 17.5)	15.1 (12.3, 18.0)	-0.35 (-2.26%)	0.840	<b>9.96 (5.43, 14.5)</b>	<b>19.2 (12.8, 25.6)</b>	<b>9.27 (93.1%)</b>	<b>0.021</b>
Bicycle	Length (km)	1.61 (1.31, 1.91)	1.13 (0.70, 1.57)	-0.47 (-29.2%)	0.078	1.09 (0.64, 1.53)	1.00 (0.36, 1.63)	-0.01 (-0.92%)	0.811
	Duration (min)	14.3 (11.7, 16.9)	10.4 (6.66, 14.2)	-3.88 (-27.1%)	0.092	9.91 (5.95, 13.9)	9.28 (3.66, 14.9)	-0.63 (-6.36%)	0.856
	CPM	1360 (1100, 1620)	1010 (629, 1390)	-351 (-25.8%)	0.131	837 (609, 1070)	609 (285, 933)	-228 (-27.2%)	0.254
	MVPA (min)	6.05 (4.92, 7.18)	4.20 (2.56, 5.85)	-1.84 (-30.4%)	0.068	4.07 (1.94, 6.20)	4.31 (1.30, 7.33)	0.24 (5.90%)	0.896

Data are presented as mean (95% CI) unless otherwise stated.

Passive Travellers (< 50% of all school trips active); Active Travellers (>= 50% of all school trips active).

CPM = Counts per minute.

MVPA = Moderate-to-vigorous physical activity.

<sup>a</sup>Adjusted using sequential Bonferroni correction.

Note. Results obtained from a generalized linear mixed model using a normal distribution and an identity link function. Fixed effects = Age, Sex; Random effects = City\*School\*Person.

## Discussion

This study investigated how school travel mode is related to physical activity across several mutually exclusive space-time domains, as well as travel behaviours for non-school trips. Our day-level results demonstrated that more physical activity was accumulated within the transport and leisure domains, and across the day as a whole, on days when adolescents travelled actively to school. Our person-level analyses revealed that school travel mode was also related to the travel mode of non-school trips: individuals who regularly travelled actively to school spent less time in vehicles on weekdays, and accumulated more MVPA during walking trips on weekend days. This study builds on existing active transport and physical activity research by furthering our understanding of how school travel is related to overall physical activity and travel behaviours.

When trips to and from school were taken collectively, they accounted for approximately 39% of total daily MVPA on weekdays, which is similar to a previous GPS-based study.<sup>271</sup> Clearly, AST makes an important contribution to physical activity needs. Our day-level results demonstrated that on any given day, adolescents were in a better position to achieve the physical activity guideline of  $60 \text{ min} \cdot \text{day}^{-1}$  of MVPA<sup>4</sup> if they engaged in AST, regardless if travelling actively one-way or both ways. This observation has important implications for studies that assess school travel as a one-way trip, as a number of individuals only utilise active travel modes on the way home from school. In fact, of the days that had one AST trip, 30% of these were trips from school. Conversely, 18.7 min of MVPA was gained in the transport domain on days that contained no AST. This suggests that on days when adolescents do not travel actively to school, they still achieve a significant proportion of MVPA while travelling actively to other destinations. This highlights the importance of accounting for total mobility in future research, rather than relying solely on the school trip.

By undertaking day-level and person-level analyses, we were able to demonstrate the physical activity implications of AST on any given day, but also the result of regular AST over a typical school week. An important consideration is whether adolescents who generally engage in AST partake in more physical activity and active transportation overall. Our results show that adolescents who frequently engaged in AST achieved more overall physical activity on weekdays and weekend days, primarily through additional MVPA accumulated in the transport domain. After exploring transportation in further detail, we revealed differences in non-school trips on both weekdays and weekend days.

Adolescents who travelled passively to school spent more time in vehicles on weekdays, which implies they also travel passively to destinations other than school. Active school travellers gained more MVPA on weekend days from walking with a higher intensity and speed. This is suggestive of purposeful walking, and may be indicative of walking for transport.

When considering the distribution of MVPA across domains, most MVPA was accumulated during transport, which is true for both active and passive travellers on weekdays and weekend days. In a similar study, Canadian adolescents living in urban areas were found to achieve the largest proportion of their MVPA during active commuting, while those living in rural areas accumulated most of their MVPA at school and home.<sup>26</sup> Similarly, in a sample of Danish youth, transport accounted for the largest proportion of MVPA in adolescents.<sup>272</sup> From these findings, we can conclude that transportation can be the biggest contributor to adolescent's daily MVPA, but this may be dependent on various environmental factors. The availability and proximity of destinations that are important for adolescents, and the presence of transportation infrastructure that makes travelling between these destinations an attractive and feasible option likely govern how MVPA is distributed across these domains.<sup>218,273</sup>

In the current study, active travellers had slightly more MVPA and less sedentary time in the leisure domain on weekdays, and it is possible that the leisure and transport domains are intertwined; active transport destinations may also form activity locations. An individual may travel actively to a destination, such as a local park, where they may engage in active pursuits. As such, these destinations hold the potential to increase physical activity in both transport and leisure contexts. Although based on survey data, the use of multiple recreation sites in the neighbourhood has been positively associated with active transport in children and adolescents.<sup>273</sup> Particular destination types may be more important for adolescent physical activity and active transport than others, and identifying these relationships is something that future studies should consider.

### **Strengths and Limitations**

The main strength of this study was the detailed objective assessment of physical activity through time and space. By assessing concurrent physical activity and location, we were able to derive travel routes, travel modes, and build multimodal trips. By collecting both space and time information, we were able to employ domains which circumvent static

representations of place and are better able to capture the fluid nature of free-living behaviour. It is likely these types of data can be utilised in future studies that use more complex simulation models (e.g., system dynamics or agent-based modelling) which model and predict the environment's impact on behavioural outcomes.<sup>274</sup> Unlike previous active transportation studies that utilise accelerometer protocols, the physical activity during cycling trips was adjusted to provide more valid estimates of transport-related and total physical activity.

Although GPS receivers are a promising research tool, their accuracy is affected by environmental conditions, with spatial error more pronounced in urban canyon and other areas where signal degradation occurs.<sup>100</sup> Some GPS points may have been misclassified into domains, especially indoor points such as during school or at home. It is also possible that the travel mode for some trips was misclassified as it was based solely on speed; slow moving vehicle trips may have been classified as bicycle trips, especially in urban regions with high traffic volumes at peak times. It is also possible that some school trips went unrecognised if the participant made intermediary stops on the way to or from school, and remained at these locations for more than 10 minutes (threshold for combining trip segments). As alluded to previously, the spatiotemporal patterns of behaviour found in this study likely only apply to similar populations living in similar geographic environments (urban areas), so caution should be taken when generalising these findings.

## **Conclusion**

Active school travel makes an important contribution to overall physical activity on weekdays, and those who engage in AST are in a better position to meet physical activity guidelines, regardless if travelling actively one-way or both-ways. Those who regularly engage in AST also have more health promoting transportation habits out of school, by way of less vehicular travel and achieving more MVPA through walking. However, adolescents who did not travel actively to school still achieved the majority of their MVPA in the transport domain, on both weekdays and weekend days. As such, future studies should consider overall mobility patterns and the availability, proximity and importance of destinations other than school when assessing physical activity and travel behaviours.

## **Chapter 6 - Towards tailored measures of accessibility in youth: important destinations for adolescents' active travel and physical activity**

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### **Preface**

The preceding chapter demonstrated how school travel behaviours were related to wider mobility patterns and physical activity across the four domains. Travelling actively to school put participants in a better position to achieve physical activity guidelines, and these individuals seemed to have more favourable transportation habits outside of school. However, adolescents who did not travel actively to school still achieved most of their physical activity in the transport domain, suggesting they may have walked to places other than school. Chapter 6 attempts to elucidate these findings by examining the full gamut of destinations that adolescent's frequent, and how reported travel to these destinations is related to physical activity in the transport domain. This chapter also seeks to demonstrate that not all destinations are equal, and some may be more important for adolescent mobility and physical activity.

## Abstract

**Background:** Recognising elements of the built environment that encourage active travel is considered a priority, yet associations among commonly assessed built environment features and active travel are by no means consistent. Beyond school, little is known about the types of destinations that adolescent's frequent, and how travel to these is related to physical activity. This study aimed to demonstrate how reported travel to destinations is related to objectively-assessed transport-related physical activity, and illustrate how visit frequency differs by destination type, as an indicator of destination importance.

**Methods:** In a sample of 196 adolescents, information about regularly visited destinations was gathered using an interactive online mapping survey. Reported travel mode and frequency were used to calculate the proportion of weekly trips travelled actively. Transport-related physical activity was objectively captured using accelerometry and GPS receivers over a 7-day period. Generalised linear mixed-effect models were used to test the association between reported travel mode to destinations and objectively assessed transport-related physical activity on both weekdays and weekend days.

**Results:** The destinations visited by the most participants were own schools (100% of participants), supermarkets (92%) and convenience stores (83%). The most visited destinations overall were participants' own schools (5.04 trips per week), friends' houses (2.97), sporting activities (2.85), and public transit facilities (1.88), while the least visited were laundries, bookstores, post offices, and banks (0.04–0.19 trips per week). Those who reported travelling actively for at least 70% their weekly trips walked further and travelled less distance in vehicles on both weekdays and weekend days, compared to those who travelled actively less than 20% of the time.

**Conclusions:** Our findings show that those who utilise active travel modes for a greater proportion of their weekly trips accumulate more transport-related physical activity and spend less time in vehicles. This work also revealed that some destinations are visited more frequently than others, and may be more important for active travel outcomes. As such, commonly used measures of walking potential (e.g., walkability) may be limited in scope, as all destinations are treated as an equal opportunity. Future work could make pragmatic use of our findings by developing more tailored measures of accessibility in youth.

## Introduction

The rise in chronic health conditions over the last few decades has coincided with a marked decline in the physical nature of daily routines.<sup>275,276</sup> In particular, we have seen a significant decline in the number of walking and cycling (active travel) trips among young people.<sup>277</sup> This is concerning as adolescents living in urban areas accumulate the majority of their moderate intensity physical activity through active travel, as opposed to structured activities at school or elsewhere.<sup>26,272,278</sup> Accordingly, recognising and understanding elements of the built environment that encourage active travel is considered a priority.<sup>17</sup> Reviews indicate that associations among commonly assessed built environment features and measures of active travel and physical activity are by no means consistent.<sup>22,24</sup> The inability to objectively capture travel-specific physical activity, coupled with the uncertainty as to how best evaluate the active travel conduciveness of an area has undoubtedly contributed to these discrepancies.

Understanding how the environment is related activity behaviours is challenging as physical activity occurs across multiple domains: household, occupation/school, leisure time, and transportation.<sup>20</sup> There is often a conceptual mismatch between environmental attributes and these domains, such as correlating the presence of recreation facilities with transport-specific outcomes. It was recommended more than a decade ago that researchers should match domain-specific physical activity to environmental attributes that conceptually influence that behaviour.<sup>194</sup> Simply, the capacity to predict behaviour is enhanced when behavioural outcomes are closely aligned with environmental variables related to that behaviour.<sup>24</sup> For example, the ability to access destinations on foot undoubtedly has a stronger association with transport-related physical activity, as opposed to total daily physical activity. This mismatch has been highlighted as one of the major limitations of the current body of reviewed evidence.<sup>279</sup>

Likewise, the active travel potential of an environment has been evaluated in numerous ways, predominantly using measures of accessibility—defined as the ability to access relevant opportunities or activities.<sup>106</sup> It has been common for health researchers to employ the walkability index (or variants of) developed by Frank *et al.*<sup>149</sup> This index consists of four urban form measures: street connectivity, residential density, land-use mix, and retail floor area ratio. Collectively, these gauge the potential of an area to be walkable, and how easily destinations can be accessed on foot. However, these indices disregard actual destinations used by individuals, which are the primary reason for travel.

They also fail to acknowledge that different destinations may be more important than others, particularly for different population groups. For example, convenience stores and restaurants would both be considered commercial land use, but convenience stores likely afford greater active travel potential for young people.<sup>154</sup> It is also possible that some destinations may only be utilised in the accompaniment of friends,<sup>280</sup> but little is known about travel companions, and how these vary by destination type. Obtaining more precise information about destination use may assist the development of accessibility measures with higher predictive ability.

To this end, interactive online mapping technologies are fast becoming of interest to health researchers. They provide an interface to capture peoples' interaction with their environment from their own perspective, including visited locations, travel behaviours, and companionship.<sup>33,218</sup> Recent advances have also been made in accelerometer and Global Positioning System (GPS) data processing methodology, making it possible to obtain objective and context-specific physical activity information in a relatively automated fashion.<sup>103</sup> In this study, we propose to gather information about regularly visited destinations (destination type, travel mode, frequency, companionship) using an interactive online mapping survey, and capture transport-related physical activity using accelerometry and GPS receivers. The aims of this study are twofold: 1) to demonstrate how reported travel to destinations is related to objectively-assessed transport-related physical activity; and 2) to illustrate how visit frequency is distributed across destination types, as an indicator of destination importance. It is hoped this information will show how destinations use is related to physical activity, but also provide evidence to stimulate the development of more tailored measures of destination accessibility in youth.

## **Methods**

### **Participants**

Adolescents (aged 12–18 years) who participated in this study were a subsample (n = 196) of those recruited for the Built Environment and Adolescent New Zealanders (BEANZ) study. The BEANZ recruitment methodology has previously been described in detail.<sup>34</sup> Briefly, adolescents were recruited from seven secondary schools in Auckland and Wellington cities, which are two of the most populated cities in New Zealand (1.5 million and 0.4 million residents, respectively). Initially, socioeconomic status (SES) and

walkability indices were calculated for all participants at the selected schools based on their home addresses. These scores were organised into tertiles, and the highest and lowest tertiles were retained. All participants residing in one of these strata were invited to participate. This sampling strategy was chosen to maximise heterogeneity in the built environment and SES variables. From this pool of consenting students, a stratified subsample of approximately 30 students per school was selected to balance participants across the four strata. Written informed consent and assent was obtained from each parent and adolescent (respectively) prior to participation. Ethical approval was granted by the Auckland University of Technology Ethics Committee.

## **Procedure**

Each school provided a space (such as an empty classroom) where participants met with the research team at a specified time during school hours. Participants were called in groups of 4–5 and were first asked to complete an interactive online mapping survey (VERITAS) with one-on-one researcher supervision. Afterwards, each participant was fitted with an accelerometer and GPS receiver using an elastic waist belt. The accelerometer was positioned over the right hip, and the GPS receiver was placed alongside in a small pouch. Each participant was taught how to wear the devices and how to charge the GPS receiver before they went to sleep at night. The equipment was collected from the school eight days later, at which point each participant received a \$20 shopping mall voucher thanking them for participating.

## **Instruments**

### ***Interactive online map***

VERITAS (Visualisation and Evaluation of Route Itineraries, Travel destinations and Activity Spaces) is a web-based interactive mapping survey which integrates Google Maps within other survey questions. The development of VERITAS for the BEANZ study is detailed elsewhere.<sup>245</sup> Firstly, participants were asked to locate where they lived, followed by the destinations they travelled to regularly within the previous six months. A list of potential destination types was provided to help stimulate recall. After placing each destination point on the map, participants were asked how often they visited this location (reported as times per week, month or year), their usual travel mode and travel

companions. Standard Google Maps features were available so participants could pan the map, zoom in or out, search for addresses, make use of Google Street View, and set the base map as either a simple road map, satellite imagery, or a hybrid of the two. All survey and map data were saved to a secure server at the completion of the survey.

### ***GPS receiver***

GPS receivers can determine their position on earth by triangulating signals received from orbiting satellites. By logging this information over time, movement across space can be recorded. The QStarz BT-Q1000XT is a commercially available GPS receiver known to have high accuracy in a stationary position<sup>100</sup> and while travelling.<sup>246</sup> Using QTravel software (v1.46, Taipei, Taiwan) each device was setup to log data every 15 s to maximise the number of data points that could be stored over a one-week period.

### ***Accelerometer***

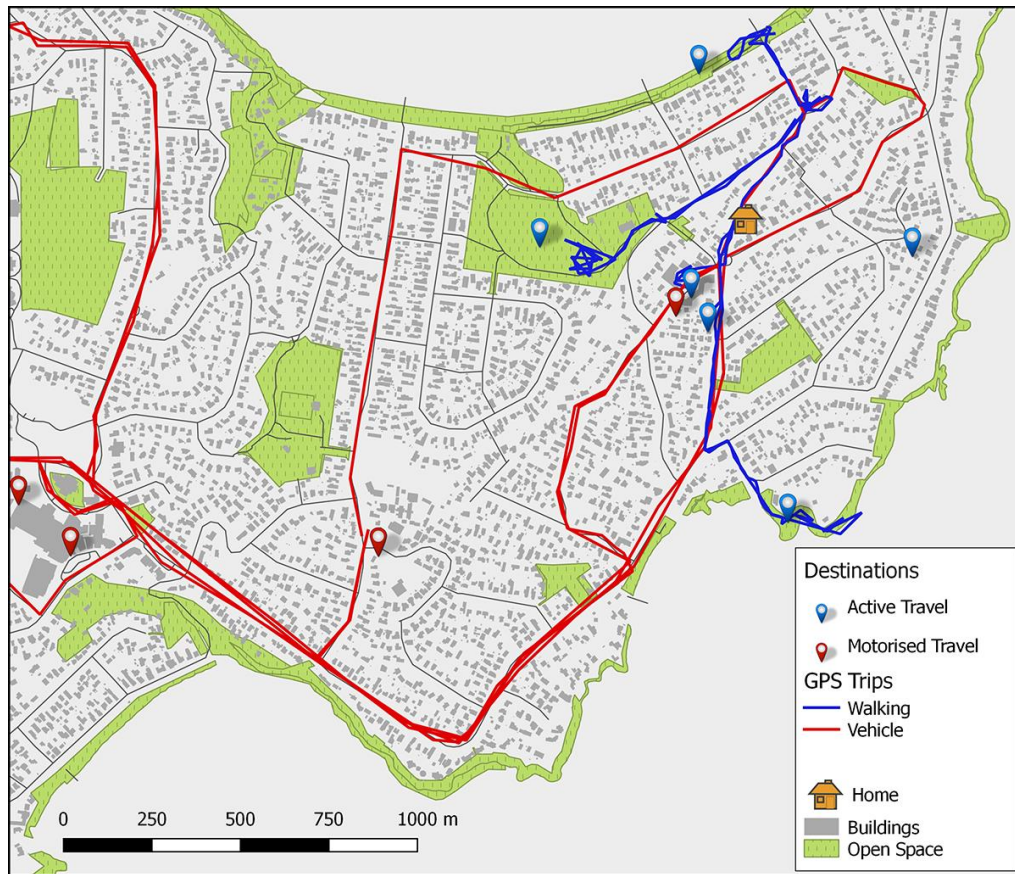
The activity monitor used in this study was the Actigraph GT3X+ (Actigraph, Pensacola, FL). This monitor contains a multidirectional accelerometer capable of collecting raw acceleration information. These are small, lightweight devices, and are widely used due to their ability to assess free-living physical activity intensity over an extended period. Each device was initialised to log raw data at 30 Hz using Actilife software (v6, Actigraph, Pensacola, FL). The system time on the computer used to initialise all devices was set to Coordinated Universal Time so the internal clock of each accelerometer was synchronised with each GPS receiver to allow the matching of data points during processing.

### **Data reduction**

Accelerometer data were downloaded using Actilife software and aggregated to a 15-s epoch to match the sampling frequency of the GPS receivers. All GPS and accelerometer data were uploaded to the Personal Activity Location Measurement System (PALMS; <https://ucsd-palms-project.wikispaces.com>): a web-based tool designed to merge multiple time-stamped data streams, and disaggregate discrete trips from GPS data. Prior to trip identification PALMS removed all points with a speed above 130 km·h<sup>-1</sup>, a change in

elevation greater than 1000 m, or points with less than 10 m of movement over three sequential fixes. A trip was classified as a series of points that spanned at least 100 m over a minimum period of 2 min. Each GPS point was categorised as indoors or outdoors based on the signal-to-noise ratio (SNR). All points with a sum SNR of less than 225 were considered indoor points and were thus removed from the beginning and end of all trips. Each trip was assigned a mode of travel based on speed; at least 35 km·h<sup>-1</sup> for vehicle, and between 1 km·h<sup>-1</sup> and 10 km·h<sup>-1</sup> for walking where the 90th percentile of speeds along the trip were considered.<sup>248</sup> The end of a trip came about in one of three ways: a pause greater than 3 min, a change in travel mode, or a loss of signal. All physical activity data were classified into sedentary, light, moderate, and vigorous intensity categories using thresholds provided by Evenson *et al.*<sup>93</sup> and non-wear time was defined as 60 min of consecutive zero counts.<sup>247</sup> For each trip, the length (km), duration (min), and total minutes of moderate-to-vigorous physical activity (MVPA) were calculated, and collectively provided objective measures of transport-related physical activity.

All destinations collected during the VERITAS survey were imported into ArcGIS 10.3 (ESRI, Redlands, CA). Each destination was categorised according to reported travel mode. Walking, cycling, or scooter/skateboard (or combinations of) were considered active travel destinations. All other destinations were considered motorised travel destinations (see Figure 6–1). The distance from home to active travel destinations was calculated in ArcGIS using a combined street centreline and pedestrian path dataset, and the distance to motorised travel destinations was calculated along standard street centrelines. This was done to obtain valid estimates of walking distance. All GIS data were obtained from Land Information New Zealand.



**Figure 6–1.** An example of VERITAS-reported destinations with GPS-derived trips overlaid.

These data represent one individual, and have been slightly modified to protect participant privacy.

## Analyses

### *Travel to destinations and physical activity*

Travel frequency for each VERITAS-reported destination was normalised into times per week. For each participant, the ratio of all trips per week that were travelled actively ( $AT_{RATIO}$ ) was calculated by dividing the total number of trips per week to active travel destinations by the total number of trips per week to all destinations (e.g., 65% of all trips per week could be travelled actively). Generalised linear mixed-effect models (GLMMs) were used to test the association between travel to destinations ( $AT_{RATIO}$  quartiles) and objectively-assessed transport-related physical activity (walking MVPA, walking distance, vehicle distance) and total MVPA on both weekdays and weekend days. GLMMs were selected as they do not require normally distributed outcomes, and allow for the stipulation of random effects that adjust for the hierarchical structure of this dataset (participants nested within schools). Age and sex differences in physical activity and

active travel have previously been reported,<sup>269,270</sup> so all models were adjusted for age and sex (fixed effects). Participants were only included in analyses if they had at least three valid days of accelerometer/GPS data—defined as having at least eight hours of wear time after non-wear time removal. Only one valid weekend day was required for inclusion in weekend analyses.

### ***Destination characteristics***

Descriptive statistics were used to evaluate VERITAS-reported destination characteristics, and illustrate how visit frequency and travel companions were distributed across destination types. The total and average number of visits per week, and the proportion of participants who reported travelling with parents, friends/siblings, or alone were calculated for each destination type. The median distance to destinations was calculated separately for active and motorised travel destinations to illustrate distance impedance for active travel modes. Statistical significance was set at  $p < 0.05$ , and all analyses were conducted in IBM SPSS Statistics v23 (IBM Cooperation, USA).

## **Results**

Table 6–1 presents participant characteristics as well as compliance descriptives for both equipment wear time and information collected during the VERITAS survey. A total of 179 participants (107 male) meet the weekday inclusion criteria for physical activity analyses. Of these, 60 were excluded from weekend analyses due to insufficient wear time, resulting in the retention of 119 participants (68 male). There was approximately 12 hours of equipment wear time on valid days. On average, the VERITAS survey took 28.4 min to complete, and the total number of destinations located (not including homes) was 3061 (1190 active travel destinations).

**Table 6–1. Participant characteristics and compliance descriptives**

	Male (n = 107)	Female (n = 72)	All (n = 179)
Age (years)	15.0 ± 1.29	15.0 ± 1.20	15.0 ± 1.25
BMI (kg·m <sup>-2</sup> )	21.4 ± 3.80	22.4 ± 3.80	21.8 ± 3.78
AT <sub>RATIO</sub>	50.1 ± 29.3	39.7 ± 27.7	45.9 ± 29.0
Days with > 8 h wear time	5.17 ± 1.54	5.37 ± 1.67	5.25 ± 1.59
Weekend days with > 8 h wear time	0.96 ± 0.84	1.17 ± 0.86	1.04 ± 0.85
Wear time on valid days (hours)	11.9 ± 2.02	12.2 ± 2.16	12.0 ± 2.08
VERITAS survey time (min)	29.1 ± 11.9	27.4 ± 8.84	28.4 ± 10.0
Number of destinations located	16.6 ± 5.96	15.2 ± 5.86	16.0 ± 5.94

Data presented as mean ± SD

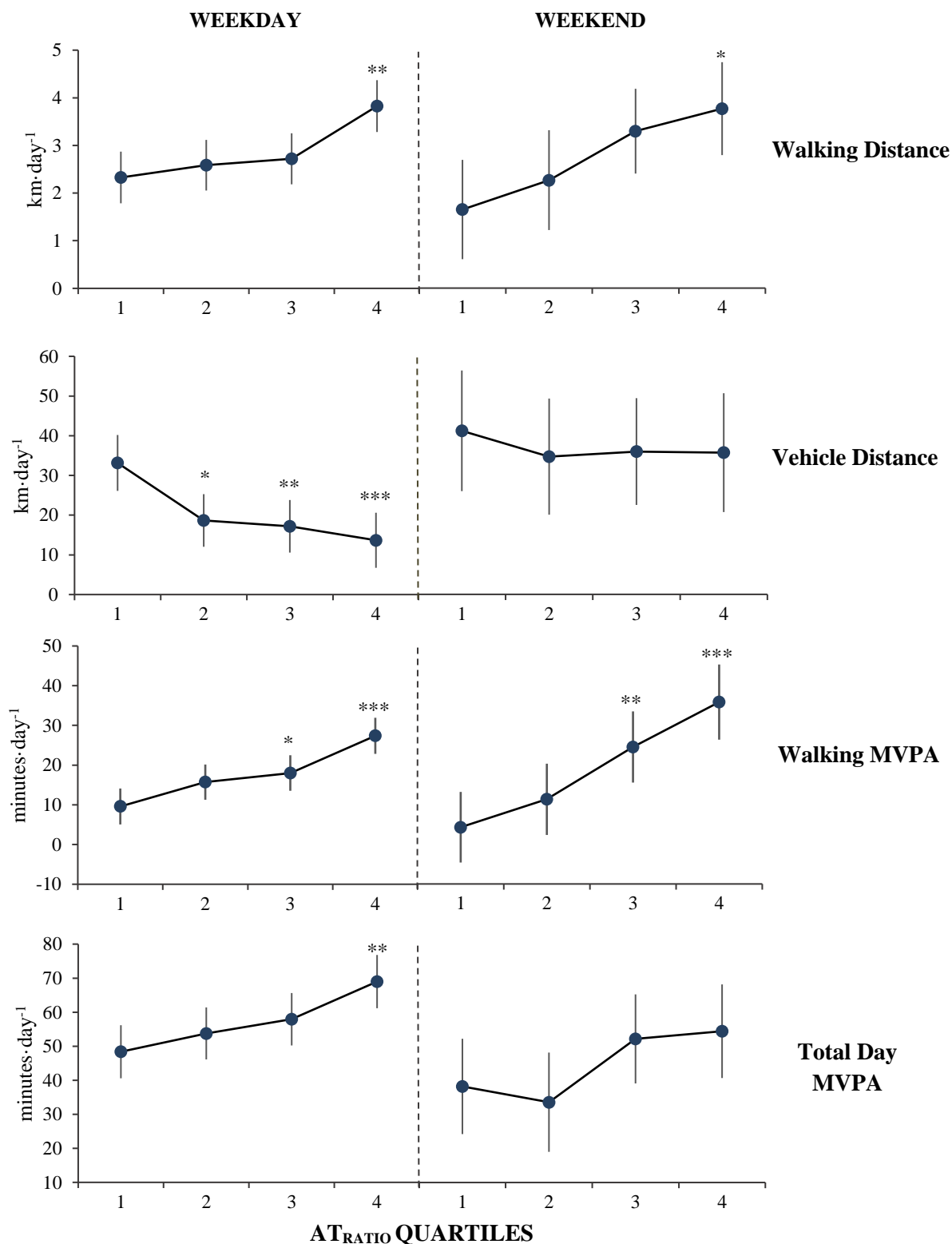
BMI = Body Mass Index

AT<sub>RATIO</sub> = The proportion of weekly trips travelled actively

### Travel to destinations and physical activity

Figure 6–2 demonstrates the association between VERITAS-reported travel to destinations (AT<sub>RATIO</sub>) and objective measures of transport-related physical activity (i.e., accumulated during GPS-measured trips), and total day physical activity (i.e., accumulated across all domains). AT<sub>RATIO</sub> is the proportion of all trips per week that were travelled actively, and was organised into quartiles (median = 44.4; 25th percentile = 21.0; 75th percentile = 69.6).

**Figure 6–2.** Association between VERITAS-reported travel and objectively-assessed physical activity.



AT<sub>RATIO</sub> = The proportion of weekly trips travelled actively.

MVPA = Moderate-to-vigorous physical activity.

Values represent estimated means and 95% confidence intervals obtained from generalised linear mixed-effect models. All models are adjusted for random (school clusters) and fixed (age, sex) effects. Asterisks represent a statistically significant difference from the first quartile:

\* (p < 0.05); \*\* (p < 0.01); \*\*\* (p < 0.001).

### ***Walking and vehicle distance***

Relative to the first quartile (Q1), those in the fourth quartile (Q4) walked 1.50 km further per weekday (95% CI: 0.45 km, 2.54 km;  $p < 0.01$ ), and 2.25 km further per weekend day (95% CI: 0.32 km, 4.18 km;  $p < 0.05$ ). Vehicle distance differences were seen between Q1 and all other quartiles on weekdays, particularly between Q1 and Q4 (-19.5 km; 95% CI: -33.1 km, -5.90 km;  $p < 0.001$ ), but these trends were less pronounced on weekend days.

### ***Walking MVPA and total MVPA***

Individuals in Q4 accumulated an additional 17.8 min of MVPA from walking on weekdays (95% CI: 9.08 min, 26.5 min;  $p < 0.001$ ) and an additional 31.5 min on weekend days (95% CI: 13.8 min, 49.1 min;  $p < 0.001$ ) compared to those in Q1. Similarly, Q4 also displayed 20.6 min more total MVPA on weekdays relative to Q1 (95% CI: 5.60 min, 35.6 min;  $p < 0.01$ ). No differences in total MVPA were seen on weekend days. It is of particular interest that the mean  $\pm$  SD walking time per day was  $50.9 \pm 35.2$  min, while the mean MVPA accumulated during these walking trips was  $16.7 \pm 15.3$  min (data not shown in Figure 6–2). This meant that only  $35.0 \pm 24.4\%$  of the time spent walking was considered MVPA.

### ***Age and sex interactions (data not shown Figure 6–2)***

Total daily MVPA showed significant interaction effects for both age and sex. Every additional year of age resulted in 4.51 fewer min of MVPA per weekday (95% CI: -7.68 min, -1.34 min;  $p < 0.01$ ). Males displayed 11.3 additional min of MVPA on weekdays (95% CI: 2.92 min, 18.6 min;  $p < 0.01$ ) and 14.2 more min on weekend days (95% CI: 0.22 min, 28.2 min;  $p < 0.05$ ) compared to females. Results were also suggestive of males walking further on weekend days (0.89 km; 95% CI: -0.10 km, 1.87 km;  $p = 0.078$ ).

## Destination characteristics

Although Figure 6–2 demonstrates that travel to VERITAS-reported destinations is related to objectively-assessed transportation and physical activity, not all destinations were reported as often, or visited as frequently. Table 6–2 presents how often each destination was reported and how frequently it was visited. The destinations visited by the most participants were own schools (100% of participants), supermarkets (92%) and convenience stores (83%). On average, the most visited destinations were participants' own schools (5.04 trips per week), friends' houses (2.97), sporting activities (2.85), and public transit facilities (1.88). The destinations visited the least frequently were laundries, bookstores, post offices, and banks (0.04–0.19 trips per week). The most active travel trips were to friends' houses (16.9% of all active trips) followed by participants' own schools (16.2%), and public transit facilities (13.2%).

**Table 6–2.** Destination visit frequency (VERITAS-reported information).

Type	Destination	People Visited n (%)	Total Trips Per Week			Average trips per week	
			Active	Motorised	Total	Visiting Participants	All Participants
School	<b>Own school</b>	192 (100)	352	616	968	5.04	<b>5.04</b>
	Another school	116 (60.4)	136	87	223	1.92	1.16
Leisure And Recreation	Park	128 (66.7)	116	31	147	1.15	0.77
	Beach	130 (67.7)	88	53	141	1.08	0.73
	Trails	83 (43.2)	93	12	105	1.27	0.55
	Basketball court	54 (28.1)	61	18	80	1.48	0.42
	Playing field	106 (55.2)	74	92	166	1.57	0.86
	<b>Organised sport</b>	143 (74.5)	122	427	548	3.83	<b>2.85</b>
	Public open space	59 (30.7)	31	27	58	0.98	0.30
	Swimming pool	89 (46.4)	30	59	89	1.00	0.46
	Indoor recreation	66 (34.4)	40	71	111	1.68	0.58
Food Retail	<b>Convenience store</b>	160 (83.3)	181	52	233	1.46	<b>1.21</b>
	Fast food	143 (74.5)	33	88	122	0.85	0.64
	Café	83 (43.2)	12	36	48	0.58	0.25
	Supermarket	177 (92.2)	40	170	210	1.19	1.09
	Restaurant	93 (48.4)	2	27	29	0.31	0.15
Other Retail	Video shop	113 (58.9)	23	45	68	0.60	0.35
	Chemist	94 (49)	8	30	38	0.40	0.20
	Post office	76 (39.6)	9	19	28	0.37	0.15
	Bank	103 (53.6)	7	29	36	0.35	0.19
	Bookstore	50 (26)	3	16	19	0.38	0.10
	Clothing store	125 (65.1)	5	83	88	0.70	0.46
	Laundry	14 (7.3)	0	7	7	0.50	0.04
	Library	115 (59.9)	33	46	79	0.69	0.41
Other	<b>Friends</b>	142 (74)	367	203	570	4.01	<b>2.97</b>
	<b>Public transit</b>	138 (71.9)	287	73	360	2.61	<b>1.88</b>
	Cultural activities	67 (34.9)	18	109	127	1.90	0.66

The five most frequently visited destinations are bolded.

Table 6–3 presents the travel companion share for each destination type, as well as the median distance to these destinations. Friends and siblings were the most common travel companion on school trips (both own school and other schools) and to all other leisure and recreation destinations. In contrast, a greater proportion of participants travelled to retail destinations in the accompaniment of a parent (apart from convenience and clothing stores). Participants mostly travelled alone to friends’ houses and public transit facilities. The median (IQR) distance was 0.87 km (0.49, 1.56) to active travel destinations (max = 5.53 km) and 3.40 km (1.91, 5.98) to all other destinations (max = 41.6 km). The distance to active travel destinations at the 90th percentile was 2.30 km.

**Table 6–3.** Companionship and distance descriptives for reported destinations.

Type	Destination	Travel Companions (%)			Travel Distance (km); Median (IQR) <sup>a</sup>	
		Parent	Friend/ Sibling	Alone	Active Travel Destinations	Motorised Travel Destinations
School	Own school	15.5	<b>56.2</b>	28.3	1.46 (0.93, 2.16)	4.67 (2.36, 12.00)
	Another school	18.6	<b>67.8</b>	13.6	0.97 (0.51, 1.59)	4.98 (2.45, 7.48)
Leisure And Recreation	Park	17.1	<b>64.6</b>	18.3	0.72 (0.36, 1.31)	3.27 (2.07, 3.84)
	Beach	36.9	<b>50.2</b>	12.9	0.8 (0.44, 1.41)	3.45 (2.24, 7.28)
	Trails	34.4	<b>43.4</b>	22.1	0.92 (0.39, 1.6)	3.87 (2.25, 8.32)
	Basketball court	13.4	<b>74.6</b>	11.9	0.82 (0.44, 1.48)	2.52 (1.99, 5.69)
	Playing field	30.6	<b>52.4</b>	17	1.19 (0.7, 2.09)	4.57 (2.84, 11.48)
	Organised sport	32.2	<b>47.8</b>	20	1.33 (0.64, 1.94)	4.68 (2.67, 7.06)
	Public open space	32.6	<b>55.8</b>	11.6	1.16 (0.33, 1.61)	5.62 (2.96, 6.94)
	Swimming pool	30.2	<b>54.3</b>	15.5	1.8 (1.12, 2.49)	4.56 (3.03, 6.11)
	Indoor recreation	27.1	<b>50.6</b>	22.4	1.68 (1.22, 2.89)	3.85 (2.44, 7.32)
Food Retail	Convenience store	15.3	<b>48.1</b>	36.6	0.58 (0.3, 1.02)	1.67 (1.01, 3.56)
	Fast food	<b>45.3</b>	43.5	11.2	0.77 (0.38, 1.31)	2.99 (1.63, 4.97)
	Café	<b>46.1</b>	46	8	1.00 (0.54, 1.56)	3.28 (1.87, 6.42)
	Supermarket	<b>59.5</b>	30.8	9.7	1.09 (0.66, 1.65)	2.47 (1.49, 3.76)
	Restaurant	<b>58.2</b>	39.7	2.1	0.85 (0.74, 1.83)	4.28 (2.15, 6.94)
Other Retail	Video shop	<b>49.2</b>	36.2	14.7	1.17 (0.67, 1.72)	1.86 (1.34, 2.98)
	Chemist	<b>75.4</b>	7.6	16.9	0.78 (0.46, 1.11)	2.14 (1.36, 4.02)
	Post office	<b>70</b>	11.1	18.9	0.88 (0.44, 1.55)	2.71 (1.66, 4.08)
	Bank	<b>63</b>	13.3	23.7	1.58 (0.92, 2.55)	3.37 (2.22, 4.87)
	Bookstore	<b>50</b>	29.7	20.3	1.21 (0.73, 1.8)	4.3 (3.32, 6.04)
	Clothing store	42.1	<b>45</b>	12.9	1.68 (1.16, 3.14)	4.96 (3.41, 7.6)
	Laundry	<b>75</b>	12.5	12.5		3.66 (1.48, 6.36)
	Library	<b>37.7</b>	35.3	26.9	1.28 (0.86, 1.98)	3.63 (2.43, 5.83)
Other	Friends	13.5	39.9	<b>46.6</b>	0.68 (0.21, 1.36)	2.05 (1.17, 4.78)
	Public transit	10.5	44.2	<b>45.3</b>	0.39 (0.15, 0.71)	3.2 (1.4, 9.77)
	Cultural activities	34	<b>36.9</b>	29.1	1.82 (0.27, 2.13)	4.5 (2.44, 6.2)

<sup>a</sup>Distance for active travel destinations calculated along a combined road centreline and pedestrian path dataset, and motorised travel destinations calculated along standard street centrelines.

The most prominent travel companion is bolded for each destination type.

## Discussion

This study captured information about regularly visited destinations using interactive online mapping surveys, and combined GPS and accelerometer data to derive measures of transport-specific physical activity. We demonstrated that reported travel patterns to these destinations was associated with objective measures of transport-specific physical activity on both weekdays and weekend days. Our results also suggest that not all destination types are of equal importance: visit frequency, travel mode share, and travel companions varied by destination type. These findings build on existing work by demonstrating how mobility patterns are related to transport-specific physical activity, and how different destination types are utilised by adolescents.

### Travel to destinations and physical activity

Adolescents who reported using active travel modes for a greater proportion of their weekly trips covered less GPS-assessed vehicle distance and accumulated more walking distance and more MVPA during walking trips. These results suggest that mobility patterns are related the volume of physical activity accrued during transportation: as the mode share of active travel increases, so does the amount of MVPA. Estimates of walking distance and walking MVPA were stronger than those for total daily MVPA. It is unsurprising that clearer trends were found when  $AT_{RATIO}$  (a transport-specific predictor variable) was matched with transport-specific outcomes (walking/vehicle distance, and walking MVPA). The failure to find significant effects for overall MVPA on weekend days demonstrates that important relationships may be overlooked (i.e., type II error) when physical activity variables lack specificity. Using measures of total physical activity or even out-of-school physical activity can attenuate the association between the environment and active travel, as a person can accumulate physical activity at home, school, or during other activities which are unrelated to transportation.

Although we were able to isolate transport-related physical activity, the built environment can influence physical activity outside of the transport domain—such as at destinations themselves—which could be classified as leisure-time physical activity. Some destinations may be important for both active travel and leisure-time activity (i.e., parks), only for active travel (i.e., convenience stores) or just for leisure activities (i.e., organised sport). Importantly, an individual that lives in an area with high active travel potential (e.g., in close proximity to school and other important destinations) may not live in an

area conducive to leisure activities (e.g., no recreation areas). Promising results have been shown when using GPS data to capture physical activity at destinations,<sup>26,103</sup> making the assessment of these relationships a possibility for future work.

An important finding was the difference between walking duration and minutes of MVPA accumulated during walking trips: 65% of the time spent walking was not considered MVPA. Trip pauses would have undoubtedly contributed to this discrepancy, but it is likely some walking was below the MVPA intensity threshold. This has important implications for how we think about assessing active-travel outcomes. While the limitations of hip-mounted accelerometers during cycling are well documented,<sup>96</sup> researchers should also be aware that MVPA derived from commonly used count thresholds may not be suitable to capture walking for transport. This may be of greater concern for youth studies, as children are known to walk slower and not as straight when travelling without adults.<sup>281</sup>

### **Destination characteristics**

Studies investigating young people's active travel have focused almost exclusively on the school trip due to its frequency.<sup>28,29</sup> Nonetheless, some studies have collected travel information for a small selection of non-school destinations in children<sup>266,282-285</sup> and adolescents,<sup>145,286,287</sup> but have not reported findings stratified by destination type. We demonstrate that some destinations are clearly visited more frequently than others, and therefore provide greater physical activity opportunity. This information could be used to create more tailored measures of accessibility for predicting travel-related outcomes, whereby accessible destinations are weighted by their importance. The neighbourhood destination accessibility index for children (NDAI-C) was recently developed by applying empirically-derived weightings to destinations based on the number of visits recorded in 7-day travel diaries.<sup>154</sup> Our data offer further insight by capturing visit frequency over an extended period, as our data suggest many destinations are not visited every week.

As expected, school was the destination visited most frequently, but when travel mode was considered, friends' houses had the highest number of active travel trips. While friends' houses are clearly an important source of active travel for young people, they cannot be accounted for in universal measures of place-based accessibility because they are specific to an individual. In theory, higher residential density may indicate reduced social isolation, but this does not always mean living closer to friends. This observation

could partly explain why residential density has shown very mixed associations with physical activity in youth.<sup>22</sup> Previous studies have found that social support and living close to friends was positively associated with active travel,<sup>138,288</sup> whereas low peer-support reduced the odds of travelling actively.<sup>289</sup> An important discovery was that all leisure/recreation destinations, as well as school, were mostly travelled to with friends or siblings, while retail destinations were mostly travelled to with parents. It seems that travel companions are an important aspect of travel for adolescents, and many recreational destinations (which are arguably the most important for leisure-time activity), are less frequently travelled to alone.

Accessibility (including walkability) is typically calculated within a catchment area centred on the home address. There has been much debate as to what cost threshold (usually a certain distance or travel time) is a suitable measure of travel impedance, as these decisions can significantly affect outcomes.<sup>175,176</sup> Many studies justify threshold decisions by citing previous studies that have used these thresholds. Some thought has been given to how far adolescents are willing to walk,<sup>290</sup> but our results build on this by demonstrating how far adolescents actually walk. Overall, the median distance to active travel destinations was 0.87 km, and the 75th and 90th percentiles were 1.56 km, and 2.30 km, respectively. Previous distance thresholds employed in adolescent studies range from 0.4 km<sup>137</sup> to 8 km<sup>174</sup>. These findings may be useful for informing cost thresholds or distance decay parameters (in gravity-based models) tailored for adolescents.

### **Study Limitations**

Distance to destinations is unequivocally the strongest predictor of active travel,<sup>273,291,292</sup> and although we were not predicting travel mode—rather, estimating physical activity from travel mode—it is important to acknowledge that the distance of active travel trips is related to physical activity volume, whereby more activity is accumulated on longer trips.<sup>263</sup> It is plausible that the distance to active travel destinations, particularly those visited more frequently, could have helped explain the amount of transport-related activity that was achieved. However, accounting for active travel distance during analysis was impractical, as VERITAS and GPS data were of different temporal dimensions (i.e., not all reported destinations were visited during the 7-day assessment period). Similarly,  $AT_{RATIO}$  was certainly influenced by distance to destinations, and this ‘distance effect’ on travel mode is clearly demonstrated in Table 6–3. While this could be considered a study limitation, it does allude to the role of accessibility in travel decisions.

It is also possible that some GPS-derived walking trips were not to any destination in particular (e.g., delivering newspapers or walking for leisure) but would have contributed to their transport-related physical activity. The identification of specific origin-destination trips from GPS data may help to isolate walking for leisure. The accuracy of GPS receivers is known to vary in different environmental conditions,<sup>100</sup> so recorded travel distances may have been affected, particularly in areas with signal obstruction (e.g., urban canyons). Lastly, VERITAS survey data were self-reported, so it is possible that some information may have been reported incorrectly.

## Conclusion

By integrating online mapping, accelerometry and GPS technologies, we were able to capture adolescents' interaction with local destinations, and derive transport-related physical activity information. Our findings show that those who utilise active travel modes for a greater proportion of their weekly trips, accumulate more transport-related physical activity and travel less distance in vehicles. Associations between travel decisions and overall MVPA were less clear, demonstrating that predictor variables which are conceptually matched to outcomes lead to stronger and clearer estimates, and minimize the risk of overlooking important links. Although we show that destination *visitation* is related to physical activity, quantifying the active travel *potential* of an environment, and how this translates into realised travel behaviour is just as important for policy implication. This work revealed that some destinations are visited more frequently than others, and may be more important for active travel outcomes. As such, commonly used measures of walking potential (e.g., walkability) may be limited in scope, as all destinations are treated as an equal opportunity. Improving sensitivity of accessibility measures will give researchers more power to predict behavioural outcomes and produce evidence which can be more readily translated into policy. Future work could make pragmatic use of our findings by developing more tailored measures of accessibility in youth.

## Chapter 7 - The development of an adolescent-specific destination accessibility index for predicting transport-related physical activity

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### Preface

The preceding chapter demonstrated that reported travel to destinations was significantly related to physical activity, particularly in the transport domain. The results also suggested that some destinations were travelled to more frequently, and may be more important for active travel outcomes. Although reported travel behaviours were associated with transport-related physical activity, the ability to capture the physical activity *potential* of an area is important when exploring the links between the built environment and realised activity decisions. Recognising elements of urban design that are supportive of physical activity can inform urban planning and policy decisions. Chapter 7 takes a data driven approach by utilising the findings in Chapter 6 to create an objective and spatially-derived measure of destination accessibility that is relevant for adolescents' active travel. This chapter firstly details the development of the index, before testing how accessibility scores are associated with objectively assessed physical activity and travel behaviours.

## Abstract

**Background:** Active travel is an important source of physical activity for adolescents, but there are currently no measurement tools that assess the walking potential of an area that are tailored specifically to adolescents. This study had two objectives: (1) to develop a destination accessibility index relevant to adolescents' active travel; and (2) to determine the associations between adolescents' accessibility scores and objectively-assessed physical activity and travel behaviours.

**Methods:** Using empirical data of adolescents' travel behaviours, a spatially-derived and objective index of destination accessibility was created to quantify the walking potential of an area. Accessibility scores were calculated for 196 adolescents, who also wore a Global Positioning System (GPS) receiver and an accelerometer for seven days. A series of travel-specific variables were generated, including walking and vehicle distance, and physical activity accumulated during transport. Generalised linear models were used to examine how destination accessibility was associated with physical activity and travel behaviours.

**Results:** Each day, adolescents living in areas with high destination accessibility accumulated 13.9 min more transport-related MVPA (95% CI: 6.10 min, 21.6 min;  $p < 0.001$ ) and 9.90 min less transport-related sedentary time (95% CI: -16.3 min, -3.50 min;  $p < 0.001$ ) than those living in areas of low destination accessibility. Similarly, individuals with high accessibility walked 1.10 km further (95% CI: 0.11 km, 2.10 km;  $p < 0.05$ ) and travelled 18.6 km less in a vehicle (95% CI: -29.5 km, -7.70 km;  $p < 0.001$ ) each day than those with low accessibility. However, there were no significant differences for total daily MVPA ( $p = 0.097$ ) or total daily sedentary time ( $p = 0.423$ ) across accessibility scores.

**Conclusions:** The accessibility index we developed from empirical travel data was significantly associated with adolescents' transport-related physical activity and overall travel behaviours. Trends for total MVPA and total sedentary time were less pronounced, suggesting an element of compensation outside of the transport domain: adolescents living in areas with low destination accessibility may substitute active travel with other activity behaviours. Future work should examine how proportions of physical activity achieved in each domain vary by environmental context.

## Introduction

Increasing physical activity in youth is an important and prevalent strategy for minimising the global burden of chronic disease.<sup>28</sup> Emerging evidence suggests that environments in which adolescents live can influence their activity patterns.<sup>22</sup> Conceptual models guiding this research propose that different domains of physical activity (e.g., school, leisure, transportation, household) are affected by different built environment features.<sup>19</sup> For example, active travel (walking or cycling for transport) is associated with the directness of routes to destinations, whereas leisure time activity is related to the availability of recreation areas.<sup>22</sup> The transport domain is of particular interest for adolescents because of their developing independence and autonomy. In fact, most of adolescents' moderate-to-vigorous intensity physical activity (MVPA) is achieved in the transport domain.<sup>26,272,278</sup> Despite this, objectively quantifying an environment's conduciveness to active travel in adolescents remains a challenge.

Public health researchers have used various geographic information system (GIS) tools to objectively gauge the walking potential of an area for adults. Most common is the walkability index—a tool consisting of four urban form measures: street connectivity, residential density, land-use mix, and retail floor area ratio.<sup>149</sup> Although these indices represent how easily destinations can be reached on foot, they treat all destinations as equal opportunities, whereas, in reality, some destinations may be more important than others. For example, convenience stores and restaurants would both be considered retail land use, but convenience stores provide greater active travel potential for young people as they are visited more frequently.<sup>154</sup> Furthermore, land-use mix does not consider specific land use types, only variation of different land uses within an area. This means that different land use types may lead to the same land use mix score, masking the effect of specific destinations on walking behaviours.<sup>293</sup> The walkability index has generally shown inconsistent and sometimes contradictory associations with physical activity in adolescents.<sup>22,30</sup>

More recently, the Walk Score tool was designed to assess adults walking potential based on the proximity to actual destinations. Walk Score calculates the distance to these destinations along the street network, and uses a distance decay function where destinations within a quarter mile (5-minute walk) receive a full score, and destinations further than 1.5 miles (30-minute walk) receive no score. Destinations are organised into seven categories (Dining & Drinking, Groceries, Shopping, Errands, Parks, Schools,

Culture & Entertainment), with some categories weighted more highly than others, but these weightings are based on adult data (i.e., cafés are weighted more highly than schools).<sup>294</sup> Walk Score is only fully available in three countries at the time of writing (United States, Australia, and Canada).<sup>295</sup> Indeed, Walk Score seems to be less relevant for elderly populations,<sup>296</sup> and may not be particularly salient for youth as destinations are customised for adults (e.g., inclusive of alcohol outlets, accountants, hardware stores, and engineering consultants).<sup>297</sup>

The Neighbourhood Destination Accessibility Index for children (NDAI-C) represents a move towards population-specific measures of accessibility.<sup>154</sup> The destination weightings utilised in NDAI-C were derived from children's travel diaries, giving higher precedence to destinations that are regularly visited by children. However, unlike Walk Score, NDAI-C is calculated within a strict 800 m threshold, and all destinations present within this area are considered equal irrespective of their proximity (i.e., destinations 100 m and 800 m from home both receive a full score). Travel mode choice clearly varies as a function of distance, and evidence suggests that there are half as many active travel trips at 800 m compared to 100 m.<sup>298</sup> In adolescents, many active travel trips are also longer than 800 m.<sup>290</sup> To date, no adolescent-specific tool exists to assess destination accessibility. Improving sensitivity of accessibility measures may give researchers more power to predict behavioural outcomes. In this study, we aim to achieve two objectives: (1) to develop a destination accessibility index tailored to adolescents; and (2) to test how these accessibility scores are associated with objectively assessed physical activity and travel behaviours.

## **Developing the accessibility index**

### **Destination typology**

Destination types and weightings used in the creation of the accessibility index were derived from previously collected empirical data on adolescent's travel patterns. The procedures used to collect this data are detailed elsewhere (see Chapter 6). Briefly, travel information was collected using VERITAS, a web-based mapping survey. Participants located where they lived, followed by the destinations they travelled to and how often they visited these locations. The average travel frequency per week was calculated for each of 27 destination types. These travel frequencies were then used to inform

destination weightings in the current study. Minor changes were made to the destination categories due to the availability of GIS datasets (i.e., playing fields and parks were combined). Friends' houses were omitted as they are specific to an individual and therefore not relevant to public infrastructure provision.<sup>154</sup> This resulted in eight main destination categories and 25 subcategories (see Table 7–1). These scores were then normalised so all destination weightings totalled 100.

### Destination data sources

Destination datasets were obtained from a variety of sources including government ministries, territorial local authorities, and online databases which were deemed adequate quality (see Table 7–1). The blue space subcategory was developed by combining river and stream data obtained from Land Information New Zealand (LINZ), with coastal sand land cover information obtained from the Land Resource Information Systems (LRIS) land cover database (LCDB v4.1). Most commercial destinations were obtained from Zenbu (<http://www.zenbu.co.nz>), an extensive online New Zealand business directory consisting of more than 100,000 businesses.

**Table 7–1.** Destination categories, data sources, and weights.

#	Category	Subcategory	Data source	Weight <sup>a</sup>
1	Education	Own school	Ministry of Education	22.78
2		Another school	Ministry of Education	5.243
3	Leisure & Recreation	Park	Territorial local authority	8.723
4		Blue space	LINZ and LRIS	3.299
5		Trails	LINZ	2.486
6		Sport	Zenbu	14.78
7		Swimming pool	Zenbu	2.079
8		Indoor recreation	Zenbu	2.621
9	Financial	Bank	Zenbu	0.859
10		Post office	Zenbu	0.678
11	Food Retail	Convenience store	Zenbu	5.469
12		Fast food	Zenbu	2.893
13		Cafe	Zenbu	1.130
14		Supermarket	Zenbu	4.927
15		Restaurant	Zenbu	0.678
16	Health	Chemist	Zenbu	0.904
17		Doctor	Zenbu	0.565
18	Public Transit	Bus or train station	Territorial local authority	8.497
19	Other Retail	Video shop	Zenbu	1.582
20		Bookstore	Zenbu	0.452
21		Clothing store	Zenbu	2.079
22		Laundry	Zenbu	0.181
23		Library	National Library of New Zealand	1.853
24		Other	Zenbu	2.260
25	Other	Cultural	Territorial local authority and Zenbu	2.983

<sup>a</sup>Weight based on weekly travel frequency.

LINZ = Land Information New Zealand; LRIS = Land Resource Information Systems.

## Calculating the index

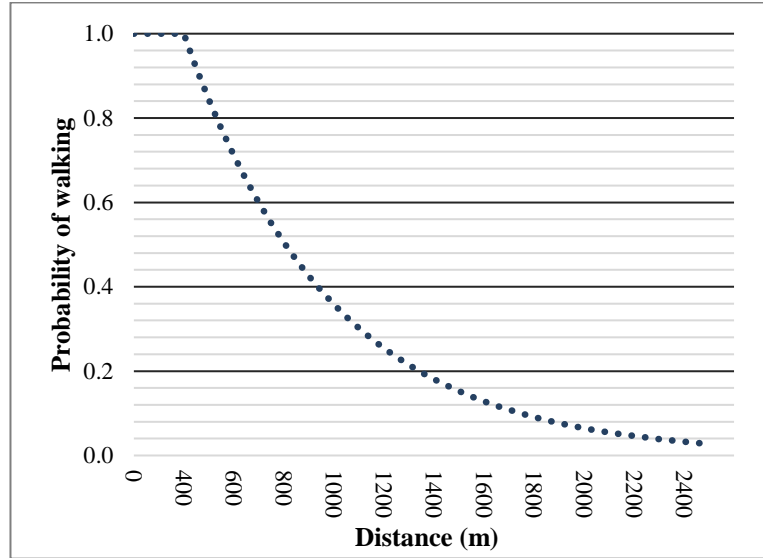
The calculation of the index was designed to be automated and easily reproducible. Using ArcGIS 10.3 (ESRI, Redlands, CA) a model was built to calculate the index from three input datasets: (1) a network dataset, (2) participant home points, and (3) destination points (Appendix F). The advantage of a model-based calculation is that certain parameters (e.g., threshold distances and destination weightings) can be easily adjusted. The index was calculated in two stages. First, all destinations deemed accessible from the participant's home were identified (see below). The original weightings of these destination were then adjusted based on their distance from home, and summed to give a final accessibility score.

At the heart of this calculation is the origin-destination (OD) cost matrix. The OD cost matrix calculates the least-cost paths from an origin to a series of destinations within a maximum search distance along a network. The computational speed is significantly faster than shortest-path analyses, as the matrix does not output true shapes of paths (i.e., path polylines are not saved, only distance). As the OD cost matrix requires point data, parks and blue space, initially represented as polygons or polylines, were converted to points prior to calculation. The network dataset used was built from Open Street Map (OSM) data using the ArcGIS OSM Editor, an open-source ArcGIS extension that can take advantage of OSM file formats. All pedestrianised features along the network were retained (e.g., footways, steps, tracks) to achieve the most realistic estimate of walking distance. A maximum threshold distance of 2300 m was selected, as this was the maximum walking distance reported during the VERITAS survey (see Chapter 6). After all accessible destinations within 2300 m were identified, the closest destination of each type was retained, so each destination type was represented binarily.

Destinations closer to home hold more significance as they are more likely to be reached via active travel; in fact, there is a curvilinear relationship between travel distance and the probability of traveling actively.<sup>299,300</sup> This phenomenon can be represented mathematically using a distance decay function: a concept in geography that explains the effect of distance on spatial interactions. An exponential equation was deemed appropriate as it declines gradually, and is therefore more appropriate for the relatively short distances seen in active travel.<sup>301</sup> A negative exponential form was used:

$$P(d) = e^{(-\beta d)}$$

where  $P(d)$  is the probability of active travel at distance  $d$ , and  $\beta$  is a decay parameter of the impedance function. A decay ( $\beta$ ) value of 1.71 was obtained from previous empirical data on adolescent travel.<sup>298</sup> Although the result of this function ranges from 0 to 1, distances shorter than 400 m automatically received a score of 1 as no VERITAS destinations within 400 m of home were travelled to in a vehicle (see Chapter 6). Figure 7–1 demonstrates this distance decay curve.

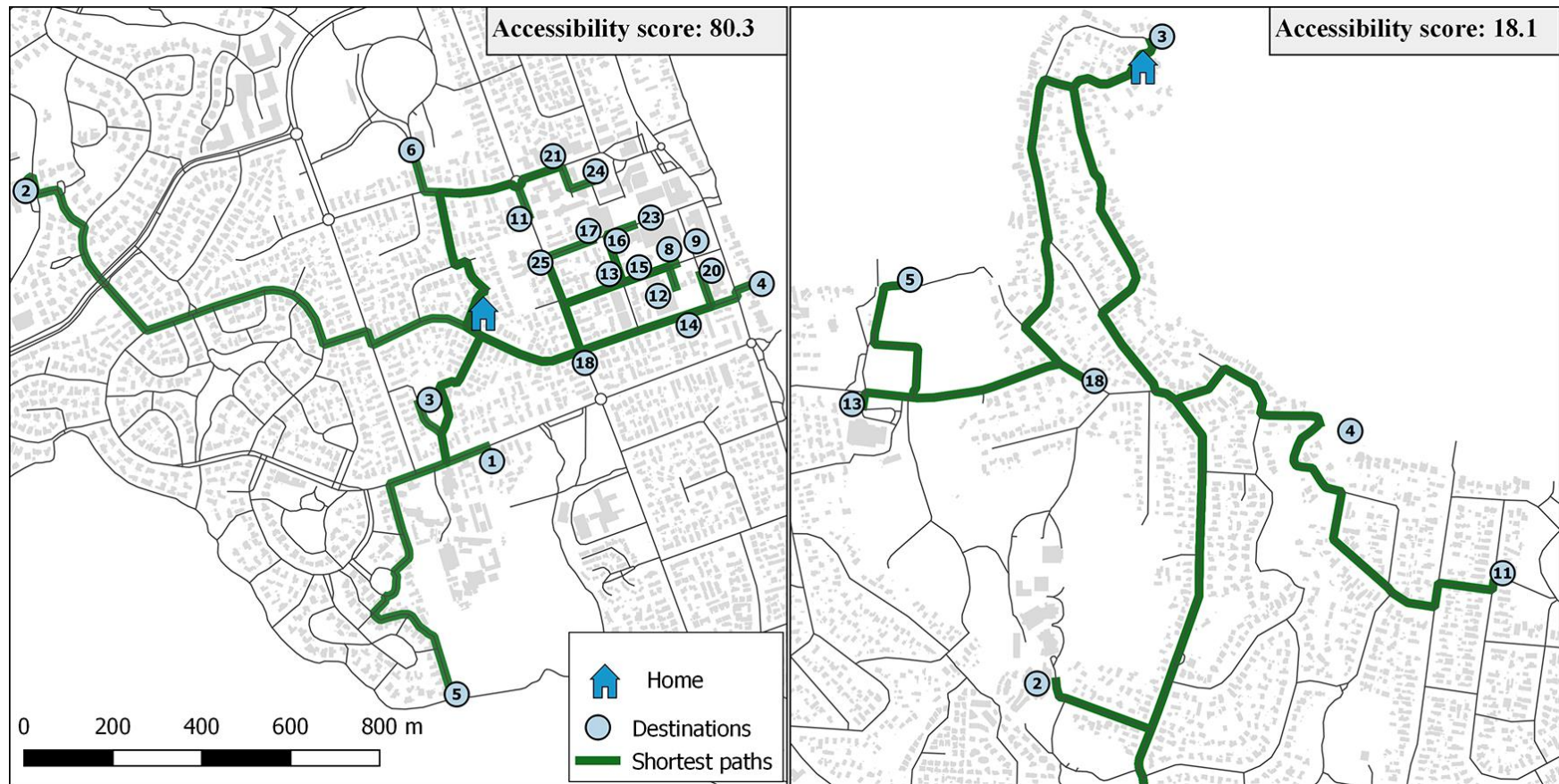


**Figure 7–1.** The exponential distance decay curve.

Initial weightings for accessible destinations were multiplied by the result of the decay function, and summed to give a final accessibility score. This can be represented by the equation:

$$A_i = \sum_j W_j f(d_{ij})$$

where  $A_i$  is accessibility score for person  $i$ ,  $j$  represents the index of all destinations within the threshold distance,  $W_j$  is the original weighting of destination  $j$ , and  $f(d_{ij})$  is the above distance decay function, calculated using the distance  $d$  from the home of individual  $i$  to destination  $j$ . The Accessibility Index score ranges from 0 to 100, with a maximum score obtained if all destination types fall within 400 m of the home. Higher scores are obtained if more important destinations are closer to home. Figure 7–2 demonstrates accessibility scores calculated for two individuals.



**Figure 7–2.** A comparison of accessibility scores for two individuals.

The destination numbers represent the destination categories presented in Table 7–1. The individual on the left lives close to several important destinations (1–school, 3–park, 11–convenience store, and 18–public transit).

## Testing the accessibility index

### Participants

Adolescents (aged 12–18 years) who participated in this study were a subsample ( $n = 196$ ) of those recruited for the Built Environment and Adolescent New Zealanders (BEANZ) study. The BEANZ recruitment methodology is described elsewhere.<sup>34</sup> In brief, adolescents were recruited from seven secondary schools in Auckland and Wellington cities, located on New Zealand's North Island. Initially, socioeconomic status (SES) and walkability indices were calculated for all participants at the selected schools based on their home address. These scores were organised into tertiles, and the highest and lowest tertiles were retained. All participants residing in one of these strata were invited to participate. This sampling strategy was chosen to maximise heterogeneity in the built environment and SES variables. Written informed consent and assent was obtained from each parent and adolescent (respectively) prior to participation. Ethical approval was granted by the Auckland University of Technology Ethics Committee.

### Instruments

#### *GPS receiver*

GPS receivers can determine their position on earth by triangulating signals received from orbiting satellites. By logging this information over time, movement across space can be recorded. The QStarz BT-Q1000XT is a commercially available GPS receiver known to have high accuracy in a stationary position<sup>100</sup> and while travelling.<sup>246</sup> Using QTravel software (v1.46, Taipei, Taiwan) each device was setup to log data every 15 s to maximise the number of data points that could be stored over a one-week period.

#### *Accelerometer*

The Actigraph GT3X+ (Actigraph, Pensacola, FL) is an activity monitor containing a multidirectional accelerometer. These are small, lightweight devices, and are widely used due to their ability to assess free-living physical activity intensity over an extended period. Each device was initialised to log raw data at 30 Hz using Actilife software (v6, Actigraph, Pensacola, FL). The system time on the computer used to initialise all devices was set to Coordinated Universal Time so the internal clock of each accelerometer was

synchronised with each GPS receiver to allow the matching of data points during processing.

## **Procedures**

Participants met with the research team at a specified time during school hours. Each participant was fitted with an accelerometer and GPS receiver using an elastic waist belt. The accelerometer was positioned over the right hip, and the GPS receiver was placed alongside in a small pouch. Each participant was taught how to wear the devices and how to charge the GPS receiver before they went to sleep at night. The equipment was collected from the school eight days later, at which point each participant received a \$20 shopping mall voucher thanking them for participating.

## **Data reduction**

Accelerometer data were downloaded using Actilife and aggregated to 15-s epochs to match the sampling frequency of the GPS receivers. All GPS and accelerometer data were uploaded and processed with the Personal Activity Location Measurement System (PALMS; <https://ucsd-palms-project.wikispaces.com>), a tool designed to clean and merge GPS and accelerometer data streams. A series of processing decisions were taken to identify individual trips and extract transport-related physical activity. A trip was classified as a series of points that spanned at least 100 m over a minimum period of 2 min. Each GPS point was categorised as indoors or outdoors based on the signal-to-noise ratio (SNR). All points with a sum SNR of less than 225 were considered indoor points and were thus removed from the beginning and end of all trips. Each trip was assigned a mode of travel based on speed; at least 35 km·h<sup>-1</sup> for vehicle, and between 1 km·h<sup>-1</sup> and 10 km·h<sup>-1</sup> for walking where the 90th percentile of speeds along the trip were considered.<sup>248</sup> The end of a trip came about in one of three ways: a pause greater than 3 min, a change in travel mode, or a loss of signal. All physical activity data were classified into sedentary, light, moderate, and vigorous intensity categories using thresholds provided by Evenson *et al.*<sup>93</sup> The length (km), duration (min), minutes of MVPA, and minutes of sedentary time were aggregated per trip. All physical activity accumulated during a measured trip was deemed transport-related physical activity. Non-wear time was defined as 60 min of consecutive zero counts.<sup>247</sup> Participants required at least eight

hours of wear time for a day to be considered valid, and at least three valid days to be included in analyses.

### **Statistical analysis**

In the first instance, descriptive statistics were generated for participant characteristics and wear time compliance. Several analyses were performed to examine how the Accessibility Index was associated with physical activity and travel behaviours. Firstly, the following day-level averages were computed per person: total MVPA (min), total sedentary time (min), transport-related MVPA (min), transport-related sedentary time (min), number of walking trips (n), number of vehicle trips (n), total walking distance (km), and total vehicle distance (km). A series of generalized linear models were used to test the association between accessibility index quartiles and the eight dependant variables described above. All models were computed using a normal distribution with an identity link function, and were adjusted for age and equipment wear time (covariates), as well as sex, participant car licence, and parental employment status (factors). Statistical significance was set at  $p < 0.05$ , and all analyses were conducted in IBM SPSS Statistics v23 (IBM Cooperation, USA).

### **Results**

Table 7–2 presents participant characteristics and equipment wear time descriptives. A total of 179 participants (107 male) meet the inclusion criteria for physical activity analyses. There was approximately 12 hours of equipment wear time on valid days, and an average of 5.2 valid days per person. Most participants (88.8%) did not hold a drivers licence, and had parents who were employed full time (50.3%). The average accessibility score was 43.7 out of 100.

**Table 7–2.** Participant characteristics and compliance descriptives by sex.

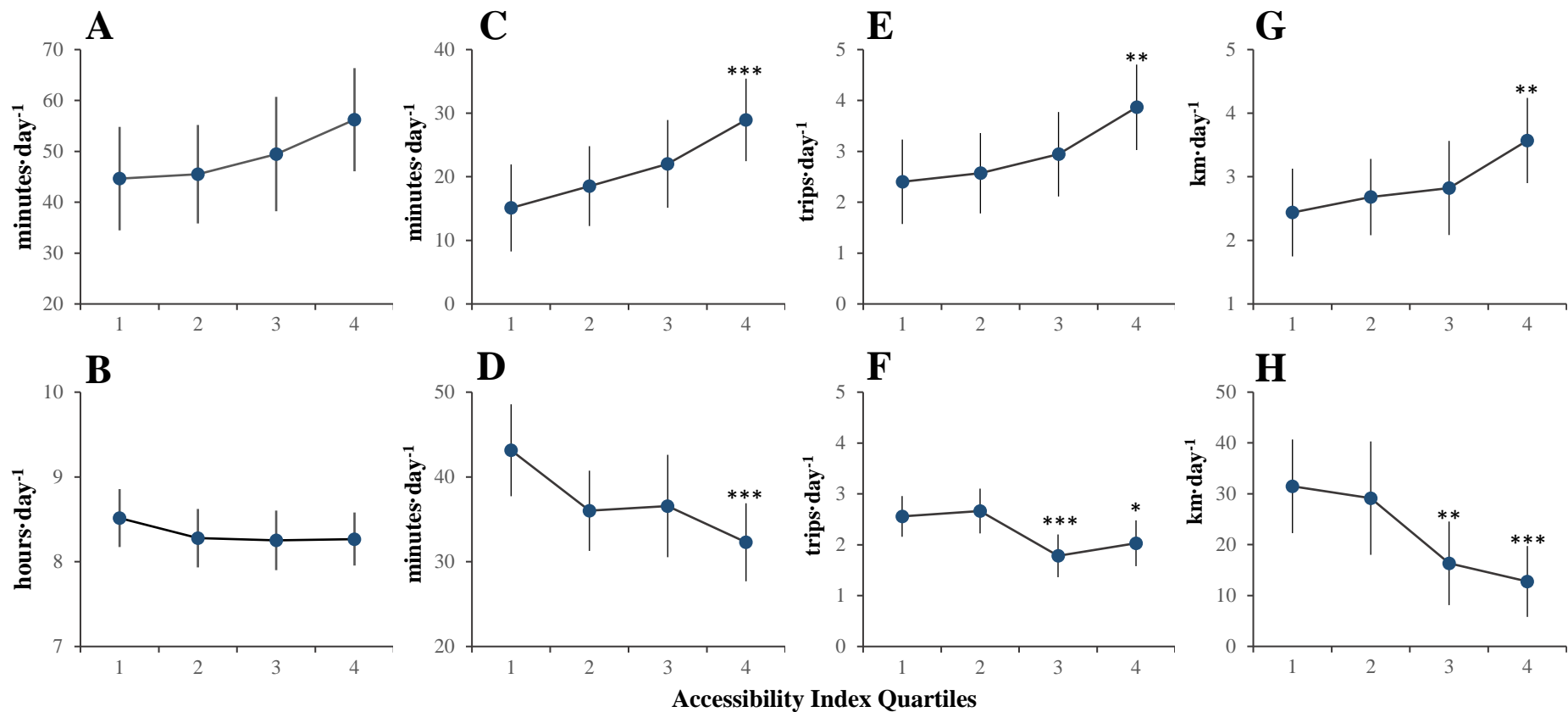
	Male (n = 107)	Female (n = 72)	All (n = 179)
Age (years)	15.0 ± 1.29	15.0 ± 1.20	15.0 ± 1.25
BMI (kg·m <sup>-2</sup> )	21.4 ± 3.80	22.4 ± 3.80	21.8 ± 3.78
Accessibility score	44.7 ± 13.7	42.3 ± 15.7	43.7 ± 14.6
Car license			
Yes	12 (11.2%)	8 (11.1%)	20 (11.2%)
No	95 (88.8%)	64 (88.9%)	159 (88.8%)
Parental employment status			
None or less than part time	17 (15.9%)	13 (18.1%)	30 (16.9%)
Part-time (16-35 hours)	34 (31.8%)	15 (20.8%)	49 (27.7%)
Full-time (35+ hours)	51 (47.7%)	38 (52.8%)	89 (50.3%)
Days with > 8 h wear time	5.17 ± 1.54	5.37 ± 1.67	5.25 ± 1.59
Weekend days with > 8 h wear time	0.96 ± 0.84	1.17 ± 0.86	1.04 ± 0.85
Wear time on valid days (hours)	11.9 ± 2.02	12.2 ± 2.16	12.0 ± 2.08

Data presented as mean ± SD or n (%) where applicable.

BMI = Body Mass Index.

Figure 7–3 presents the association between the Accessibility Index scores and objectively measured physical activity and travel patterns. The Accessibility Index scores were organised into quartiles to allow the comparison between groups (median = 45.8; 25th percentile = 31.0; 75th percentile = 55.5). Panels A and B show that total daily MVPA increases and sedentary time decreases with higher accessibility; however, these trends were not statistically significant ( $p = 0.097$  and  $p = 0.423$ , respectively). Panels C and D demonstrate clearer trends: individuals with the highest accessibility (Q4) had 13.9 more min of transport-related MVPA (95% CI: 6.10 min, 21.6 min;  $p < 0.001$ ) and 9.90 min less transport-related sedentary time (95% CI: -16.3 min, -3.50 min;  $p < 0.001$ ) per day than those with the lowest accessibility (Q1). Similarly, Panels E and F show that those in Q4 had 1.45 more walking trips per day (95% CI: 0.50, 2.41;  $p < 0.01$ ) than those in Q1, and Q3 had 0.77 less vehicle trips per day compared to Q1 (95% CI: 0.29, 1.27;  $p < 0.001$ ). Lastly, Panels G and H show individuals in Q4 accumulated 1.10 km more walking distance (95% CI: 0.11 km, 2.10 km;  $p < 0.01$ ), and 18.6 km less vehicle distance (95% CI: -29.5 km, -7.70 km;  $p < 0.001$ ) per day than those in Q1.

**Figure 7–3.** Physical activity and travel behaviours across accessibility index quartiles.



The relationship between quartiles of destination accessibility and (A) total MVPA; (B) total sedentary time; (C) transport-related MVPA; (D) transport-related sedentary time; (E) number of walking trips; (F) number of vehicle trips; (G) total walking distance; and (H) total vehicle distance.

Values represent estimated means and 95% confidence intervals. Results obtained from generalized linear models using a normal distribution and identity link function. All models are adjusted for age, sex, parental employment status, participant car license, and accelerometer wear time. Asterisks represent a statistically significant difference from the first quartile: \* (p < 0.05); \*\* (p < 0.01); \*\*\* (p < 0.001).

## **Discussion**

This study developed an accessibility index designed to capture the supportiveness of local destinations for adolescents' active travel. This index was then tested against objectively-assessed physical activity and travel behaviours in a sample of adolescents. Our results suggest that travel behaviours are associated with destination accessibility—as accessibility increases, so does the number of walking trips, walking distance, and transport-related MVPA. Contrarily, accessibility was negatively associated with vehicular travel and sedentary behaviour. This work expands our understanding of how the built environment is related to adolescents' physical activity and travel behaviours.

### **Destination accessibility, physical activity, and sedentary behaviour**

Several GPS studies have shown that a large portion of adolescents' physical activity is achieved during active travel,<sup>26,272,278</sup> or on sidewalks and streets,<sup>302</sup> which is suggestive of active travel. Our results build on this evidence by demonstrating that active travel behaviours are related to the destination accessibility of their local neighbourhood. Similarly, the number of daily vehicle trips, distance travelled in vehicles, and sedentary time accumulated during travel were all negatively associated with destination accessibility. It seems that the availability of local destinations is important for increasing physical activity and reducing sedentary time, both independent risk factors for disease.<sup>51</sup> This finding is important as environmental correlates of sedentary time are generally very mixed, as sedentary behaviour is rarely objectively measured in context.<sup>303</sup>

Associations with total MVPA and total sedentary time were less pronounced. This finding reinforces the importance of capturing domain-specific behaviour in built environment studies, and suggests accessibility measures may not be pertinent for predicting total MVPA (which is made up of all types of activity and thus has a range of influences). These results may also imply that total MVPA and sedentary time 'balanced out' across other aspects of the day, and physical activity and sedentary time are simply shifted from one domain to another in response to the built environment. For example, individuals who live in areas with low destination access may have different time-use patterns, and engage in physical activity outside of the transport domain (e.g., at home, school, or during leisure). The emerging notion of using compositional analysis techniques with 24-hour activity data<sup>304</sup> could potentially be applied to a composition of

physical activity domains. Individuals living in areas of high and low accessibility may have similar levels of sedentary time (as seen in the current study), but the proportion of sedentary time accumulated in each domain may vary (also seen in the current study). Examining how accessibility is associated with physical activity and sedentary time across domains, in relation to the environment, is a logical progression of this work.

### **Strengths and limitations of the accessibility index**

We combined concepts from the Walkability Index, Walk Score and NDAI-C to create an adolescent-specific measure of accessibility. To our knowledge, this is the first built environment measure of walking potential developed specifically for adolescents, and offers several advantages over currently available tools. Firstly, destinations are weighted by established visit frequencies, meaning the environment's supportiveness for walking is based on the types of destinations that adolescents are known to frequent. The use of actual destinations overcomes the ambiguity typical with land use based measures. It is reasonably well established that land use mix is related to physical activity, as it is a proxy of destination diversity. However, identifying specific destinations that support adolescents active travel is probably more intuitive and relevant for planning and policy decisions.<sup>154</sup> The implementation of a distance decay function bypasses the need for buffers to capture travel impedance. A buffer distance too small will exclude potentially relevant destinations, whereas a buffer distance too large runs the risk of capturing destinations that are unlikely to be reached on foot. Distance parameters used in the decay function were based on empirical data detailing how far adolescents travel.

Nonetheless, this index is not without its limitations. Only the closest destination of each type was retained, but having a choice of destinations may also be important for travel decisions. Previous research suggests more desirable parks are visited frequently even though they may not be the closest to home.<sup>305</sup> Secondly, the same distance decay function was used for all destination types, yet the willingness to travel actively may differ by destination type and trip purpose.<sup>298</sup> It must also be noted that these decay parameters were specific for walking rather than cycling—a conscious decision knowing the extremely low numbers of adolescents that cycle in New Zealand.<sup>306</sup> A distance decay curve for cycling would show a much more gradual decline, which illustrates that if cycling were to become a feasible travel mode choice (e.g., implementation of cycling infrastructure), it could minimise distance as a barrier, effectively increasing destination

accessibility. However, if this index was adapted to suit cycling, it would need to account for the cycling infrastructure present between destinations as this is linked to safety concerns.<sup>134</sup> Lastly, a higher accessibility score may not always translate into more transport-related physical activity. This is because higher accessibility scores are achieved with greater destination proximity, but less physical activity is accumulated on shorter trips. The distance decay function we implemented is based purely on the probability of walking, not the ‘ideal’ distance for maximising physical activity volume.<sup>263</sup>

## **Conclusion**

This study showed that the ability to access relevant destinations on foot is important for increasing adolescent’s physical activity and reducing their sedentary time, at least in the transport domain. Trends for overall MVPA and sedentary time were less pronounced, suggesting an element of compensation across other physical activity domains. More work is needed to understand how the environment influences physical activity outside of the transport domain, and how the proportion of activity in each domain varies by environmental context. We identified several aspects of the accessibility index that could be modified to improve the strength of association between the environment and behaviour. Future work should develop these ideas into more refined measures of accessibility, and perform sensitivity analyses to compare the predictive ability of this index with existing measures (e.g., the walkability index).

Physical inactivity is a key modifiable risk factor for chronic disease, yet 80% of young people struggle to meet physical activity guidelines globally.<sup>10</sup> Physical activity typically declines over the course of adolescence, and activity status during this life stage is predictive of health in adulthood.<sup>5</sup> Accordingly, the promotion of physical activity during formative years is important for future population health and wellbeing. The apparent difficulty in achieving physical activity guidelines may be circumvented by ‘engineering’ physical activity into daily routines; encouraging walking or cycling for transport being a common strategy. However, there is growing consensus that sustainable changes in physical activity behaviour at the population level will require multifaceted approaches that target individuals as well as the built environment.

The behavioural epidemiology framework recognises that high quality evidence must be collected before evidence-based interventions can be developed, and policies can be informed.<sup>21</sup> Despite this, current research shows inconsistent and sometimes contradictory associations between the built environment and adolescent physical activity behaviours. Overcoming several measurement-related issues are consistently acknowledged as avenues of progression.<sup>22,24,31</sup> The aim of this thesis was to explore how recent technological and methodological innovations can enhance our understanding of how the built environment is related to adolescents’ physical activity and travel behaviours. Chapters 3 to 7 present a progression of studies that design and test several novel techniques for measuring physical activity, mobility, and certain aspects of the built environment.

### **Research Summary**

Chapter 3 developed and piloted a novel online mapping tool (VERITAS) for capturing information about adolescents’ interaction with their environment. The collection of several types of geographic data were demonstrated, including visited locations, travel routes, and user-defined spaces. Data for over 500 destinations were collected from 28 participants, establishing the feasibility of this tool in an adolescent sample. Despite the low sample size, results suggested that distance, travel companions, and destination type

were all related to travel mode choice. The perceived neighbourhood boundary that participants drew was different in size and shape than traditional neighbourhood delimitations, and consequently differed in urban form scores.

Using a larger sample, Chapter 4 continued by examining how school travel routes drawn in VERITAS compared to actual travel routes assessed by GPS receiver. The process of route comparison was more challenging than anticipated, and required new GPS methodology to be developed. The identification of multimodal trips was a necessary precursor to the extraction of individual school trips, as many adolescents used multiple travel modes on the trip to school. Discrepancies were observed between drawn routes and those measured by GPS, but travel mode choice, travel mode transitions, and taking multiple routes to school explained some of these differences. Surprisingly, less than 60% of participants used the same travel mode for all their school trips, and one third reported using more than one route to school.

Chapter 5 was conceived by recognising that most research on adolescents' physical activity and travel behaviours had focused almost exclusively on the school trip. This chapter examined how school travel patterns were related to physical activity across the four physical activity domains, and if these corresponded with travel behaviours beyond the school trip. Novel data processing techniques were used to classify merged GPS and accelerometer data into the four physical activity domains. Travel mode to school was related to out-of-school physical activity and transport practices, but those who did not travel actively to school still achieved most of their physical activity in the transport domain. It was concluded that examining destinations beyond school could provide further insight on the determinants of physical activity and travel behaviours.

Chapter 6 used the online mapping techniques piloted in Chapter 3 to survey the entirety of destinations that adolescents visit regularly. This study demonstrated how reported travel mode to these destinations was related to objectively-assessed physical activity in the transport domain. Those who reported using active travel modes more often accumulated more transport-related physical activity, spent more time walking and less time in vehicles on both weekdays and weekend days. Travel companions varied by destination type, and some destinations were visited more frequently than others. It was concluded that wider mobility patterns were important, and that lack of specificity in accessibility measures (i.e., the walkability index treating all destinations as an equal opportunity) may have contributed to mixed findings in previous research.

Chapter 7 made pragmatic use of the findings in Chapter 6 by creating a measure of destination accessibility that was relevant to adolescents' active travel. The accessibility scores were based on the distribution of destinations around the home, accounting for both destination type and the distance from the residence. Reported visit frequencies were used to develop destination weightings, and destinations further from home received a lower score by way of distance decay. Destination accessibility scores were significantly associated with physical activity in the transport domain, but not total physical activity across the day, suggesting an element of displacement across other physical activity domains. This study demonstrated the importance of assessing domain-specific physical activity in built environment studies.

## **Significance of findings**

This body of work makes several novel contributions to the physical activity and built environment field, particularly in the measurement realm through improved specificity. Each of these contributions and their implications are discussed below.

### **Online mapping techniques for capturing adolescent mobility behaviours**

Online mapping applications are an emerging method in health research and are yet to be widely implemented in this field. The VERITAS tool was originally designed for French adults in the RECORD study,<sup>33</sup> and similar methodologies have been used in Finnish children.<sup>218</sup> The work presented in this thesis is the first to use online mapping to assess mobility in New Zealand, and the first to adapt these techniques and trial them in an adolescent sample. Chapters 3 and 4 demonstrated the functionality and feasibility of the VERITAS tool, while Chapter 6 used these data to describe several novel aspects of adolescent mobility. For the first time, we were able capture the full gamut of regularly-visited destinations including their geographic location, something that is impractical and cumbersome to measure with travel diaries or short-term GPS records. By doing so, we gathered much needed empirical travel information which was used inform a new measure of destination accessibility. Collectively, this research has revealed that online mapping is a practical solution for capturing certain aspects of adolescents' behaviour, and these data offer unique insights into adolescents' mobility within their local sphere.

This work serves a grounding for future studies, as it is likely these methods will become more commonplace in health research in the years to come.

### **Integrating GPS and accelerometry to capture context-specific physical activity**

The use of GPS receivers in health and transportation research dates back to the early 2000s,<sup>307,308</sup> yet another five years passed before the integration of accelerometer and GPS data first appeared.<sup>309,310</sup> The development of PALMS<sup>101</sup> made it easier to manage large spatial datasets without programming expertise, and consequently, more GPS-based physical activity studies started to appear from 2010 onwards. At the conception of this thesis, only four studies had integrated GPS and accelerometer data in adolescents: one focusing on methodology,<sup>311</sup> two examining general locations of physical activity,<sup>104,130</sup> and the last demonstrating how time spent at various locations differed in urban and rural contexts.<sup>26</sup>

In built environment research there is greater capacity to predict behavioural outcomes when they are matched with environmental variables specific to that behaviour.<sup>24</sup> The socioecological model of the four physical activity domains provides a structure to formally conceptualise this paradigm, and hence formed the basis of this work. Chapter 5 classified physical activity into the four domains (home, school, transport, and leisure), while Chapters 6 and 7 took a more focused approach by isolating transport-related physical activity to better understand the environmental determinants of travel decisions. Chapter 6 showed that reported destination visitation was related to transport-related physical activity, while Chapter 7 showed that the active travel potential of an area was related to realised physical activity and travel behaviours. Importantly, both studies show weaker or non-existent associations between these variables and total physical activity. This observation has important implications for existing and future work, as it illustrates associations between the built environment and physical activity can be overlooked with measures that lack specificity (e.g., total physical activity). This ‘dilution’ phenomenon has been speculated for many years,<sup>194</sup> but these are among the first studies to show this effect with a much greater level of precision.

Chapter 4 was the first study to automate the construction of multimodal trips from GPS and accelerometer data. This was done for the sole purpose of extracting specific origin-destination trips (in this case home-school trips) with greater accuracy. However, this also opens many possibilities for objectively capturing detailed multimodal travel

information such as transit use (e.g., travel mode transition points, wait times, physical activity accumulated during walking segments). To date, walking associated with transit use has received little attention, even though transit use is important for sustainable development and numerous health indicators.<sup>249</sup> To date, most evidence is based on self-reported or travel diary estimates,<sup>312</sup> although a recent study that objectively assessed adolescent walking during school transit trips found that nine minutes of MVPA was achieved during transit walking, which was no different than purely walking trips.<sup>313</sup> Despite not being a main objective, Chapter 5 found comparable results with six minutes of MVPA accumulated during walk-vehicle trips, and 13 minutes during purely walking trips. However, car trips with a short walk would have been included in these estimates, which may have lowered the MVPA attributable to transit.

Another novel finding related to walking was the discrepancy between minutes of walking and minutes of MVPA accumulated during waking trips—approximately 65% of the time spent walking was not considered MVPA. As discussed in Chapter 6, trip pauses would have contributed to this difference, but it is likely some walking was below the MVPA intensity threshold. This has vital implications for how we think about assessing active-travel outcomes, as any real effects of the built environment on travel behaviours may be overlooked if active travel is not adequately captured. The moderate intensity accelerometer threshold used in this research (2296 CPM) was developed from a series of lab-based activities including walking at different speeds.<sup>93</sup> Walking at 2 mph averaged 1179 CPM while walking at 3 mph averaged 3096 CPM. Clearly, slower walking might be missed, but it is still important for health as it offsets time spent sedentary.<sup>314</sup>

### **Physical activity and school travel**

This work demonstrated that active school travel (AST) accounted for approximately 39% of total daily MVPA on schooldays, which is similar to previous GPS-based studies.<sup>271,315</sup> However, we also identified that two thirds of participants did not engage in AST regularly, but these individuals still achieved most of their physical activity in the transport domain. Chapter 6 expanded these findings by showing school was the most frequently visited destination, but other destinations cumulatively accounted for more weekly trips. The average length of AST trips was ~1.5 km, but the average length of all

school trips was close to 3 km, with many significantly longer, suggesting that walking to school is not practical for many.

Much research and policy effort has been invested into initiatives such as School Travel Plans and Safe Routes to School<sup>316</sup> with the implicit assumption that these interventions will produce meaningful increases in population physical activity. In New Zealand, adolescents spend around 190 days in a calendar year at school, and many live too far from school for walking to be practical travel mode choice. A recent review concluded that AST can make a meaningful contribution to MVPA on individual schooldays for those who travel actively, but to make a substantial contribution to *population* MVPA, the prevalence of AST will have to increase markedly.<sup>317</sup> This is not helped by the relaxation of school zoning to increase parental choice in schooling, and the growing numbers of private schools in Auckland—both likely contributors to an increase in the average distance between home and school.<sup>318</sup> Nevertheless, approximately three quarters of school trips were still within 6 km, so cycling-specific initiatives may be a tactic that should receive more attention (discussed below).

### **Mobility in the wider context**

This was first study in New Zealand to show that adolescents who had better access to destinations from their place of residence spent less time in cars, more time walking, and therefore accumulated more MVPA and less sedentary time in the transport domain. However, the suburban sprawl typical in major New Zealand cities has caused destinations to be further apart, increasing car dependency, and consequently, reducing accessibility by active means.<sup>69</sup> In Chapter 7 we suggested that if cycling were to become a feasible travel mode choice, it could minimise distance as a barrier, effectively increasing destination accessibility and thus opportunities for physical activity. However, commuter cyclists have been declining in New Zealand since the 1980s, with the biggest declines seen among young people.<sup>319</sup> Despite this downward trend, children and adolescents have shown the greatest increase in the risk of cycling injuries over the last few decades.<sup>320</sup> It is perhaps unsurprising that traffic safety concerns are a main deterrent for adolescent cyclists.<sup>134,138,306</sup>

Data from the Netherlands—a country which has invested heavily in cycling since the 1970s—show that 63.6% of adolescents living further than 5 km from school still choose to cycle.<sup>321</sup> Netherlands and other European nations have made cycling a safe, convenient

and practical travel mode choice through the coordinated implementation of multifaceted, mutually reinforcing policies. These include the provision of pedestrian and cycling infrastructure, people oriented urban design, public transit integration, car use restrictions, and giving cyclists the right of way.<sup>322</sup> It is evident that the uptake of cycling has positive benefits, but only if cycling is made a safe, easy, and efficient alternative to passive forms of travel. The New Zealand government has recently allocated NZD \$100 million to the Urban Cycleways Programme<sup>15</sup> which is a promising step forward. Nonetheless, infrastructure alone may not be sufficient to change travel behaviours if safety perceptions do not also change.<sup>134</sup> The placement and design of cycling infrastructure, and the degree of traffic separation are likely important factors for changing safety perceptions. Future research is required in these areas, particularly as urban and transport planning discussions become more inclusive of active travel policy and design.

The implications of active travel modes go beyond favourable physical activity patterns; wider benefits include less noise and air pollution, climate change mitigation, urban vitality, and numerous financial benefits. Auckland and Wellington cities are the second and third worst congested cities in Australasia behind Sydney, and this is considered by the OECD as a significant bottleneck to New Zealand's economic expansion.<sup>323</sup> New Zealand's population is projected to grow by 1.5–2% (70,000–94,000 people) annually, and Auckland city is expected to account for 60% of this growth.<sup>324</sup> Auckland's Unitary Plan suggests that over 400,000 new homes will be built over the next 23 years, including retrofitting existing urban form to increase density, and expansion into new greenfield developments. During this process, it will be important to preserve recreation areas and public spaces that offer important physical activity opportunities for adolescents, consider accessibility to relevant destinations, and evaluate school placement in new residential developments.

## **Study limitations and future directions**

In addition to the limitations discussed within each research chapter, there are several wider limitations of this work that must be noted. Firstly, this research used a cross-sectional study design, and hence causality cannot be inferred. However, stronger study designs (such as randomised controlled trials) are challenging as randomisation is virtually impossible in this field; researchers are rarely able to manipulate environmental or policy factors. The strongest level of evidence is obtained from prospective evaluations

of physical activity before and after people relocate to areas of different urban form.<sup>279</sup> This is also challenging and costly in the real world, so the opportunistic evaluation of ‘natural experiments’ is encouraged.<sup>325</sup> Natural experiments evaluate the efficacy of changes to the built environment that are not instigated by the researcher, such as the construction of new facilities or revitalisation of existing areas.<sup>326</sup> These designs are thought to provide stronger evidence of causality, and capitalising on these opportunities is now considered a research priority.<sup>327</sup> Despite this, natural experiments are often met with methodological and conceptual obstacles, including the uncertainty in defining and measuring exposure to the intervention, and unravelling precise causal pathways.<sup>326,328</sup> The measurement methodologies presented in this thesis may offer solutions to these problems, but additional work is required to test their applicability to specific natural experiments. The planned growth and revitalisation of several urban communities in New Zealand (e.g., the Northcote redevelopment in Auckland) present exciting opportunities for future work.

Secondly, it must be acknowledged that the conceptualisation of the built environment was limited across studies; there are several aspects of the built environment relevant to travel decisions that were not considered (e.g., aesthetic qualities, pedestrian infrastructure). Furthermore, despite being grounded in the socioecological model, this research focused primarily on the physical nature of the environment, and paid relatively little attention to the personal and social aspects of behavioural decisions. Behaviours materialise from the interplay between these multiple factors, not just the built environment.<sup>19</sup> As mentioned earlier in this chapter, adolescents’ perceptions of safety is an important driver of travel mode choice.<sup>134</sup> Parents may also act as ‘gatekeepers’ by constraining behaviour based on their own observations of environmental safety;<sup>166,167</sup> although, this seems to be more pronounced in younger children rather than adolescents.<sup>168</sup> Despite not focusing on the interaction among these factors, the work presented in this thesis did demonstrate that physical activity and travel behaviours were related to age and gender, and that travel companions varied by the type of destination visited. This research also demonstrated the applicability of online mapping tools, which are a unique medium to gather motivations, opinions, and preferences about certain aspects of the environment. These tools go some way towards bridging the inner layers (personal and social factors) and outer layers (built environment) of the socioecological model, and hold considerable potential for explaining why certain behaviours occur.<sup>218,220</sup> However, quantifying the interplay and relative importance of individual, social, and

environmental factors is challenging, but the use of structural equation modelling to unravel these interactions is becoming more prominent.<sup>329-331</sup> Future research should explore ways to integrate these types of qualitative information with detailed behavioural patterns gathered from sensor-based equipment.

This work predominantly focused on physical activity in the transport domain, but the physical activity domains are intertwined; as time spent in one domain increases, time spent in another domain must decrease. Chapter 7 alluded to this by showing that individuals with high destination accessibility achieved more MVPA in the transport domain, but total MVPA was similar to those living in areas with low destination accessibility. Adolescents who are inactive in transport domain are not necessarily inactive individuals, they may simply spend their time differently and engage in physical activity elsewhere.<sup>26</sup> Examining how certain elements of the built environment are associated with the proportion of physical activity achieved in each domain is a logical progression of this work. This process is complementary to the recent move towards understanding 24-hour activity patterns.<sup>332,333</sup> This is based on the premise that combinations or patterns of behaviours (e.g., sleep + activity + sedentary time) may interact to impact health in ways that cannot be explained by studying these behaviours in isolation. This is because each component is part of a finite whole (i.e., 24-hours) meaning a change in one component will have flow-on effects to other components in the composition (e.g., time in the transport domain is substituted with time in the leisure domain). These types of data require specific analysis strategies, and emerging compositional analysis techniques are promising in this regard.<sup>304</sup>

Lastly, there are several factors that may limit the generalisability of findings. Due to the exploratory nature of this work, a priori sample size calculation was not performed. However, the ideas presented in this thesis (i.e., reducing measurement error) may have implications for sample size calculations in future work.<sup>334</sup> This research focused on two of the most populous cities in New Zealand because urban planning and policy decisions will have the most impact in these areas; however, adolescents living in more rural areas may have markedly different mobility patterns.<sup>26</sup> Furthermore, the accessibility index developed in Chapter 7 was tested in the same population from which the destination weightings were derived (i.e., from Chapter 6). Despite being a data driven approach, it is possible this could have strengthened the association between accessibility scores and physical activity, and reduced its generalisability to the wider adolescent population. Hence, future work could not only develop these ideas into more refined measures of

accessibility, but trial these measures in an independent sample, and compare the predictive ability of this index with existing measures. It should also be noted that any built environment or policy change can affect all people, not just adolescents. The importance of certain destinations or features of the built environment may vary across groups. Older adults are increasingly viewed as a key population who are less mobile and more susceptible to built environment change,<sup>335</sup> particularly in terms of the design and quality of pedestrian facilities.<sup>336</sup> This is particularly relevant for New Zealand given its aging population.<sup>35</sup> Consequently, future work is required make sure built environment and policy decisions have a positive impact for all New Zealanders across all life stages.

## **Conclusion**

This thesis has demonstrated how recent technological innovations can enhance our understanding of how the built environment is related to adolescent's physical activity and travel behaviours. This work represents an original contribution to the current body of knowledge in physical activity and built environment research. A central theme of this thesis was need for more specific measures of physical activity, and the inclusion of built environment variables that were conceptually matched to physical activity domain. Through integrating interactive online mapping, GPS, accelerometry, and GIS technologies, we captured overall mobility patterns and objective measures of domain-specific physical activity; two methodological constraints of previous work. Our novel results demonstrated how these techniques can advance this field of research, and highlighted the importance of measurement specificity, particularly from an inferential standpoint. This body of work has reinforced the importance of active travel for New Zealand adolescents, and has established the links between destination accessibility, transportation and physical activity behaviours. It is hoped the information contained within this thesis will contribute to the next generation of physical activity studies, and help inform the development of more compact cities that promote active living and reduce health inequities.

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## Appendixes

### Appendix A. Thesis subsample descriptives

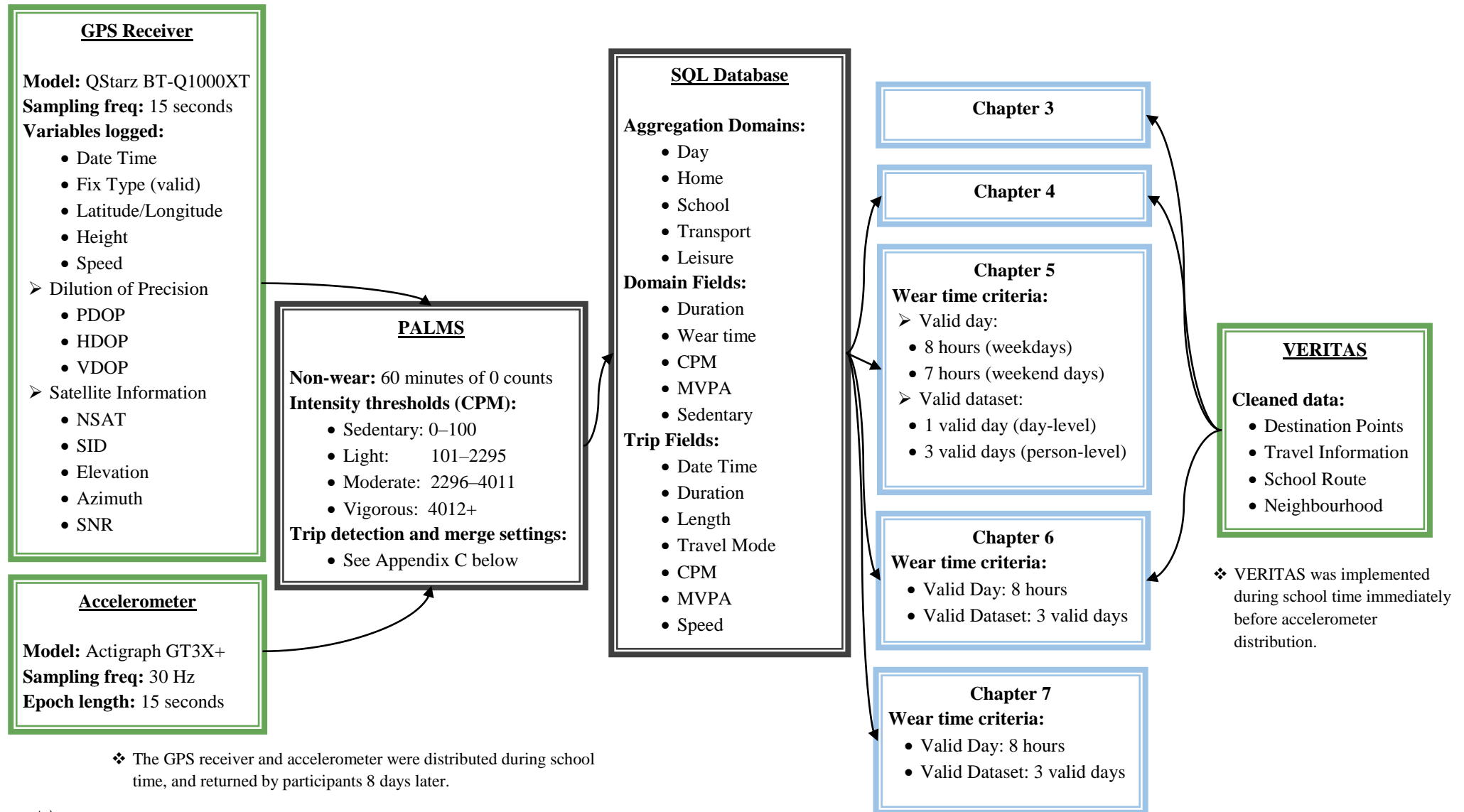
		BEANZ Sample <i>n</i> = 515	Thesis Subsample <i>n</i> = 197	<i>p</i> <sup>a</sup>
Age		15.18 ± 1.42	14.98 ± 1.23	0.062
Height		167.9 ± 8.82	167.3 ± 9.12	0.409
Weight		60.96 ± 12.45	61.63 ± 14.42	0.567
BMI		21.54 ± 3.65	21.89 ± 4.05	0.290
Gender	Male	327	116	1.000
	Female	230	81	
School Year	9	165	57	< 0.001
	10	122	74	
	11	132	27	
	12	67	21	
	13	59	11	
Ethnicity	NZ European	338	139	0.023
	NZ Maori	18	14	
	Pacific	19	3	
	Asian	67	13	
	Other European	32	15	
	Other	37	11	
SES/Walkability	Low/Low	58	16	0.111
	Low/Mid	50	22	
	Low/High	42	26	
	Mid/Low	66	17	
	Mid/Mid	76	22	
	Mid/High	26	15	
	High/Low	105	35	
	High/Mid	45	16	
	High/High	26	6	

Continuous data presented as mean ± SD and categorical data presented as frequencies

BMI = Body Mass Index; SES = Socioeconomic status

<sup>a</sup>P value of difference (independent samples t-test or chi-square where appropriate)

## Appendix B. Data processing decisions and workflow



❖ The GPS receiver and accelerometer were distributed during school time, and returned by participants 8 days later.

❖ The belt-worn accelerometer was positioned on the right hip, and the GPS receiver was worn alongside in a small pouch.

## Appendix C. PALMS optimisation settings

GPS Settings		
Loss of Signal	Max duration allowed (seconds)	600
	Remove lone fixes	Check
Filter invalid Values	Filter invalid values	Check
	Max speed (km·h)	130
	Max change in elevation	1000
	Min change in distance required over 3 fixes	10
Indoor Detection	Detect indoors	Check
	Max satellite ratio when indoors	50
	Max SNR value when indoors	225
Trip Detection	Min distance travelled over 1 minute	25
	Min trip length	100
	Min trip duration	120
	Min pause time	120
	Max pause time	180
	Max % of trip allowed within a single location	100
	Max % of trip allowed indoors	75
	Remove indoor points from trip start and ends	Check
Location Detection	Include trip pauses at locations	Uncheck
	Trap indoor points within locations	Uncheck
	Trap outdoor points within locations	Uncheck
	Trap points that are part of a trip	Uncheck
	Allow locations without trips	Uncheck
	Reset location numbers for each participant	Uncheck
	Cluster radius	30
	Min time at location	300
Mode of Transportation	Vehicle speed cut-off	35
	Bicycle speed cut-off	10
	Walk speed cut-off	1
	Percentile of speeds to consider	90
	Classification segment length	30
Compute Averages	Compute Average speeds	Uncheck
	Compute Average elevations	Uncheck
	Number of GPS Samples to average	3

Accelerometer Settings		
Accelerometer	Include accelerometer	Check
	Use vector magnitude (if available)	Uncheck
Non-wear time	Mark not wearing time	Check
	Minutes of zeros in a row	60
Activity bout detection	Detect activity bouts	Check
	Minimum bout duration (minutes)	10
	Activity bout upper limit	9999
	Activity bout lower limit	2295
	Activity bout tolerance (minutes)	2
Sedentary bout detection	Detect sedentary bouts	Check
	Sedentary bout duration (minutes)	30
	Sedentary bout upper limit	180
	Sedentary bout tolerance (minutes)	1
Activity classification cut-off values	Very hard cut-off value	99999
	Hard cut-off value	4012
	Moderate cut-off value	2295
	Light cut-off value	100

Merge Settings		
Merge Options	Merge data to GPS	Uncheck
	Start first day at midnight	Uncheck
Missing GPS Fixes	Insert missing fixes	Check
	Insert until max duration	Check
	Max number of seconds to insert	600
Mark Events	Mark trips	Check
	Mark pause points	Check
	Mark location changes	Uncheck
	Mark activity bouts	Check
	Mark sedentary bouts	Check

## Appendix D. Published manuscripts

Stewart et al. *International Journal of Behavioral Nutrition and Physical Activity* (2015) 12:18  
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### RESEARCH

### Open Access

## A novel assessment of adolescent mobility: a pilot study

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### Abstract

**Background:** The accurate measurement of daily mobility and travel to destinations beyond the residential neighbourhood has been identified as an important but almost systematically overlooked factor when investigating the relationship between exposure to the built environment and physical activity. The recent development of VERITAS – a web-based application nested within a computer-assisted personal interview – allows researchers to assess daily mobility, travel to regular destinations, and perceived neighbourhood boundaries using interactive mapping technology. The aims of this pilot study were to (1) demonstrate the feasibility and functionality of using VERITAS in an adolescent sample, and (2) compare urban form characteristics and geometric features of the perceived neighbourhood with traditional neighbourhood delimitations.

**Methods:** Data were collected and analysed for twenty-eight participants (14 male,  $15.9 \pm 1.48$  years) in 2013. Participants underwent anthropometric assessment before completing a custom-designed VERITAS protocol under the supervision of trained interview technicians. Regularly visited destinations, school travel routes, transportation modes, travel companions, and perceived neighbourhood boundaries were assessed. Data were imported into ArcGIS and street network distances between the home and each geolocated destination were generated. Convex hull activity spaces were derived from destinations. Urban form variables and geometric characteristics were compared between the perceived neighbourhood, existing meshblocks, 1 mile Euclidean buffers, and 1 km network buffers.

**Results:** In total, 529 destinations were geolocated, 58% of which were outside the perceived neighbourhood boundary. Active travel was inversely associated with distance to destinations ( $r = -.43, p < .05$ ) and traveling with adults ( $r = -.68, p < .01$ ). Urban form and geometric characteristics of the perceived neighbourhood were different from those in other neighbourhood delimitations.

**Conclusions:** This study demonstrates the feasibility of using VERITAS to assess mobility within adolescent populations. Our results also illustrate the potential novelty and use of user-defined spaces, and highlight the limitations of relying on restricted definitions of place (i.e., administrative or residential-focused neighbourhoods) when assessing environmental exposure.

**Keywords:** Active travel, Adolescent, Built environment, Mobility, Neighbourhood definition, Physical activity, Spatial polygamy, VERITAS, SoftGIS

### Background

Physical inactivity is a key contributor to the widespread prevalence of non-communicable disease [1]. Behavioural and motivational approaches to increase physical activity have had relatively limited effectiveness [2], causing researchers to consider how environmental and policy factors may affect behaviour and health [3]. An accurate

assessment of environmental exposure is paramount for the clarification of these relationships and the development of supportive policy. The environment contiguous to the principal residence is unquestionably important when investigating interactions with the environment, but current methods of neighbourhood delimitation are equivocal [4], and the residential neighbourhood is not the sole mechanism that links place to health [5].

Previous health studies have estimated environmental exposure using predefined administrative area subdivisions

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[6,7], ego-centred definitions of space; such as buffers of varying distances and types around the principal residence [4], and mental maps [8,9]. However, the environment to which individuals are exposed may differ substantially from these 'residential neighbourhood' type measures: individuals are not normally confined within these spatial boundaries, and visit an array of destinations beyond the perimeter of their residential neighbourhoods (known as spatial polygamy) [10]. Having focussed exclusively on residential neighbourhoods as an area delimitation to assess environmental exposures, the majority of these studies have succumb to the 'local trap' [11], and overlooked the concept of spatial polygamy, resulting in a potential mischaracterisation of environmental exposure [12].

The everyday movement of individuals over space between destinations, known as daily mobility, has been recognised as an important component that needs to be accounted for in the assessment of environmental exposure [13,14]. Mobility is also important for identifying the shape and scale of exposure, which may vary between different population groups. For example, the proportion of daily mobility trajectories inside and outside the neighbourhood may differ between adults and youth or adolescent groups who interact more with their local resources and infrastructure. Mobility is not only important to enhance the assessment of environmental exposure, access to resources, and feelings of neighbourhood belonging [15], but also as a potential source of active transport [16]. A recent study showed adolescents living in urban areas accumulated 57% of moderate-to-vigorous physical activity (MVPA) while commuting to activity places, rather than at the destinations themselves [17].

Activity spaces have been proposed to characterise the spatial patterns of mobility [5,18]. Activity spaces are expressions of spatial behaviour which enclose the principal residence, the destinations where individuals spend their time, and the travel routes between these destinations [19]. These measures are thought to be more comprehensive spatial summaries of mobility and experienced spaces compared to traditional neighbourhood measures [5]. Activity spaces are commonly derived from convex hulls [20], standard deviational ellipses [21] or travel time polygons [18] and likely encompass environments both inside and outside the residential neighbourhood, yet only 4% of studies in a recent review investigated both [13]. The few studies that have included locations outside the neighbourhood have mainly focused on fixed spatial daily life centres, such as the workplace or school, yet minor activity locations and the travel between them are also of interest [5]. Significant differences between environmental characteristics within the neighbourhood and beyond the neighbourhood have been shown [22] justifying the use of activity spaces in addition to residential neighbourhood measures.

Early evidence for daily mobility was primarily collected using retrospective mobility surveys [23], and later real-time travel diaries [24] where participants were asked to keep detailed accounts of all trips made. However, detailed information requires a high level of participant engagement and accuracy, which increases participant burden and can lead to incomplete and incorrect information [25]. Even though these data can be used to estimate trip lengths, frequencies, and travel modes, there is an absence of the exact itineraries followed [26]. With technological advances, the use of portable Global Positioning System (GPS) receivers to measure outdoor movement is becoming a more feasible and cost-effective solution [27]. Although GPS receivers can obtain a comprehensive record of spatiotemporally referenced data, GPS measurement is still somewhat hindered by technological constraints, such as signal dropout, memory limitations and poor battery life [28]. Furthermore, the cleaning and processing of GPS data requires significant time and expertise [29], which may limit the size and scale of GPS studies, although improved methods are rapidly reducing the significance of these problems [30]. More recently, electronic activity location questionnaires with integrated interactive mapping capabilities have been proposed to enhance the geographic accuracy of data, ease of collection, and the possibility of collecting additional information such as perceived spaces or limits of independent mobility [16]. Such approaches offer a practical alternative for mobility assessment, and have shown high convergent validity when compared with GPS travel records [20,31].

The Visualization and Evaluation of Route Itineraries, Travel Destinations, and Activity Spaces (VERITAS) is a web-based application delivered within a Computer-Assisted Personal Interview (CAPI) that integrates interactive mapping functionality (based on Google Maps) with traditional activity and travel questions [16]. This enables participants to accurately geolocate regular destinations inside and outside of the residential neighbourhood, answer questions related to each of those destinations, and draw lines and polygons indicative of routes and spaces. VERITAS can assess daily mobility over extended retrospective periods, which may provide more relevant comparisons with chronic health indicators such as BMI. VERITAS was initially proposed and developed for the RECORD Study – a longitudinal study focusing on the links between the environment and health in French adults [32] – and has yet to be trialled within an adolescent sample.

The aims of this pilot study were to (1) demonstrate the feasibility and functionality of using VERITAS in an adolescent sample, and (2) compare urban form characteristics and geometric features of the perceived neighbourhood with traditional neighbourhood delimitations. It is hoped this information will contribute to the next

generation of built environment and mobility studies, and help elucidate the links between the built environment, physical activity, and health.

## Methods

### Participants

Twenty eight adolescent participants (13 – 18 years) were recruited from an Auckland high school as a subsample of participants in the Built Environment and Adolescent New Zealanders (BEANZ) study – a cross-sectional study exploring the links between the built environment and health in New Zealand adolescents. The BEANZ recruitment procedures are described in detail elsewhere [33]. Briefly, New Zealand meshblock (smallest census tract unit) walkability indices were calculated for all eligible participants based on their residential addresses, which were obtained from the school's database prior to the consent process. The walkability indices used were consistent with previous research in New Zealand adults [34]. The subsample was selected from the pool of consenting students, with half of the sample randomly selected from the lowest walkability tertile and the remaining half from the highest tertile in an attempt to achieve variation in environmental exposure [34]. Ethical approval was granted by the Auckland University of Technology Ethics Committee (AUTC), and written informed consent was obtained from each student and parent prior to participation.

### Instruments

VERITAS-BEANZ was developed by translating VERITAS-RECORD from French to English. The conception of VERITAS-RECORD is described in more detail elsewhere [16]. Elements of the NEWS-Y [35] questionnaire were incorporated and adjusted to suit the New Zealand adolescent sample (i.e., including netball and rugby league as sporting options, and push scooters as a mode of travel option). VERITAS-BEANZ has five successive parts: (1) locating the principal residence (and secondary residence if necessary), answering questions about its occupants, and recording the level of neighbourhood attachment on a 1–6 Likert scale, (2) selecting the types of places visited in the previous six months from a list of destination categories (e.g., school, bank, post office), (3) geolocating the most frequently visited destination within each of the selected destination categories (e.g., the post office visited most frequently), and answering questions related to that destination; such as visit frequency, mode of travel, travel companions, and whether they are allowed to go there without adult supervision, (4) plotting the usual route travelled to school (and from school if necessary) by placing a series of points which connect to form a polyline (Figure 1), and (5) plotting their perceived neighbourhood

boundary by placing a series of points, which connect to form a polygon (Figure 1).

Unlike VERITAS-RECORD, plotting the perceived neighbourhood boundary occurred after geolocating regular destinations. It is possible that the dispersal of previously located destination markers may influence a participant's perception of their neighbourhood, yet this order of steps was selected in hopes it would improve the accuracy of the boundary delimitation. Before plotting their perceived neighbourhood, their principle residence was positioned at the centre of the map. Participants were then asked to "draw a shape which you feel represents your neighbourhood" and were ensured there were no right or wrong answers [36].

Participants identified frequently visited destinations from a list of 33 categories extracted from the NEWS-Y questionnaire, as well as dedicated questions for sport, cultural and religious activities, and visiting friends. To assist with destination identification, VERITAS-BEANZ is equipped with Google Street View and embedded search tools which can identify destinations of a particular type (or from key search terms) within a given radius (Figure 1). Altogether, VERITAS-BEANZ contains a maximum of 188 individual questions (some of which may have multiple answers); although participants do not have to answer questions related to destinations they have not visited.

### Procedure

Data collection took place at an Auckland high school in June 2013 over a 3 day period. Height was measured to the nearest 0.1 cm using a portable stadiometer (SECA 213, Hamberg, Germany), weight to the nearest 0.1 kg using electronic scales (SECA 813, Hamberg, Germany) and waist circumference at the navel to the nearest 0.1 cm using a Lufkin Executive Thinline steel tape measure (W606PM, Cooper Hand Tools, NC, USA) in line with ISAK-developed protocols [37]. Trained interview technicians took each participant through VERITAS-BEANZ on a laptop computer which was connected to the school's wireless local area network (Wi-Fi). During the interview, any questions or aspects of VERITAS which participants had trouble understanding were made note of, and discussed with the research team at the conclusion of each day's data collection session. Answers and map data were automatically saved to our dedicated server during and at completion of the interview.

### Data reduction

VERITAS-BEANZ questionnaire data (mode of travel, frequency of visits, travel companions) and map data (destination, polyline, and polygon coordinates) were downloaded and imported into ArcGIS 10.1 (ESRI, Redlands, CA, USA). Perceived neighbourhood boundary



**Figure 1** Google Maps tools embedded within VERITAS-BEANZ.

coordinates were then converted to polygons using the ET GeoWizards (ET Spatial Techniques, Faerie Glen, Pretoria) point to polygon conversion tool. The shortest network route between the principal residence and each mapped destination was estimated using the Network Analyst Extension and street centreline data obtained from the Land Information New Zealand (LINZ) database ([www.linz.govt.nz](http://www.linz.govt.nz)). Using VERITAS-BEANZ questionnaire data, each of these estimated travel routes were coded as either active travel (i.e., walking, cycling), passive travel (i.e., motorised transport) or mixed travel, which was defined as a combination of both passive and active travel (whether individual trips were multimodal, or different travel modes were used for different trips). All frequency of visits data (reported as either times per week, month, or year) were all converted to times per year for comparative purposes. Using the distance, frequency and mode of travel, a weighted distance metric was computed to estimate the annual distance accumulated by each mode of travel, whilst travelling to each destination.

1 mile Euclidian buffers, 1 km network buffers and corresponding meshblocks were generated for the purpose of comparing the perceived neighbourhood. These buffer distances were chosen because they have commonly been used in adolescent samples [38–42]. A convex hull is a minimum bounding geometry technique which encloses multiple geographic features within the smallest possible convex polygon [20], and was used to define activity space by enclosing all geolocated destinations. Excluding

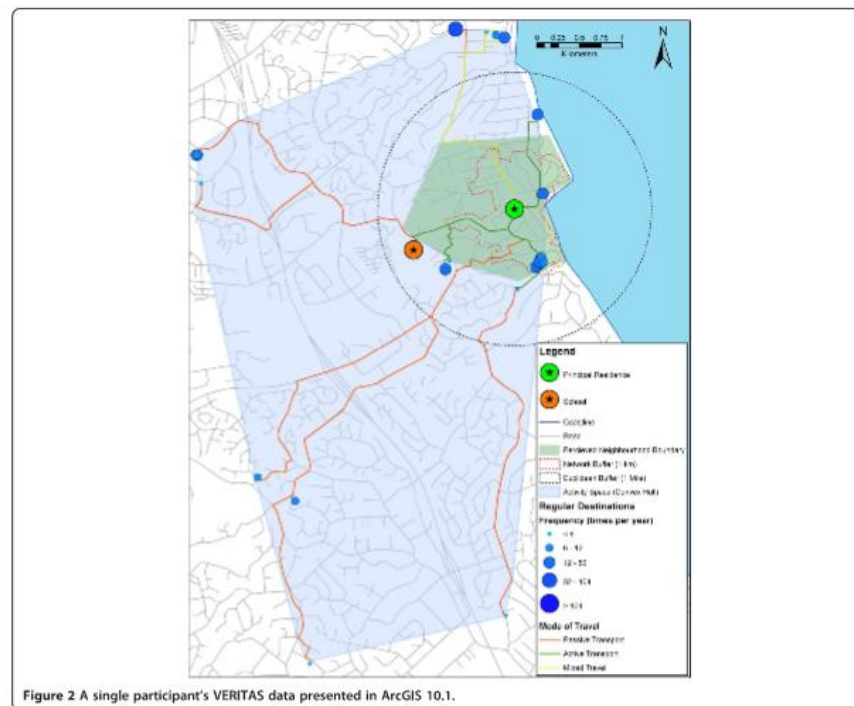
destinations which are visited rarely may provide more representative spatial summaries of typical travel behaviour, but due to the pilot nature of this study, all destinations that were located during the BEANZ-VERITAS questionnaire were included in the activity space delineation (Figure 2). The ArcGIS XY to line and Generate Near Table tools were used to calculate the distance from the principal residence to the farthest boundary vertex, and the distance to the closest edge of each neighbourhood delimitation and activity space. The uniformity of each neighbourhood polygon around the principal residence was assessed using the ratios of these two distances along with shape circularity. Circularity is a measure of how closely a shape resembles a circle, and is defined as the ratio of the area of a shape with the area of a circle which has the same perimeter [43]. Circularity was calculated using the equation:

$$\text{Circularity} = 4\pi A/P^2$$

where  $A$  is the area and  $P$  is the perimeter of the shape. The circularity ratio ranges from 0 to 1, the latter indicating a perfect circle [44]. For each neighbourhood delimitation, the percentage of area that overlapped the perceived neighbourhood was also calculated.

#### Measures of urban form

Urban form variables have been inconsistently associated with adolescent physical activity in the past [45], although the imprecise assessment of the residential neighbourhood



**Figure 2** A single participant's VERITAS data presented in ArcGIS 10.1.

may have contributed to these discrepancies [4]. Three distinct measures of urban form (land use mix, street connectivity, and residential density) were calculated within each of the neighbourhood delimitations. Auckland Council zoning data were used to calculate land use mix. Land was categorised as residential, commercial, industrial, open space, or other. Entropy scores were used to calculate the extent of land use mix using the equation:

$$Land\ Use\ Mix = -1 \left( \sum_{i=1}^n P_i * \ln(P_i) \right) / \ln(n)$$

where  $n$  is the number of different land use categories and  $P_i$  is the proportion of land use category  $i$  in the region. Entropy scores range from 0, which indicates no mix or homogeneous land use, to 1 which represents heterogeneous land use, or a perfect mix. Street connectivity was estimated by calculating the number of intersections with three or more intersecting streets

per square kilometre. Intersections were extracted from pedestrian road network data (i.e., with non-walkable elements such as highways and on/off ramps removed). All intersections within 10 m were considered one intersection to account for roads that may not align perfectly. As meshblock boundaries are normally defined by street centrelines, a 20 m buffer was applied to each meshblock to include peripheral intersections which may otherwise be omitted. The number of private dwellings per meshblock was obtained from the New Zealand 2006 census [46]. Residential density for each meshblock was calculated by dividing the total number of private occupied dwellings by meshblock area. Residential density was calculated within each polygon and buffer by estimating the number of private dwellings using an area weighted average based on meshblock-level data. The handling of these urban measures was consistent with previous studies [34].

### Analysis

Descriptive statistics (mean  $\pm$  SD) were generated for all data. Normality tests revealed non-normally distributed data so nonparametric analyses were performed. Wilcoxon signed rank tests were used to assess differences between residential neighbourhood delimitations, Mann-Whitney U tests were used to assess differences between genders, and Spearman's correlations were used to test for associations between trip distances, travel modes and travel companions. Significance was set at  $p < .05$ , and all analyses were conducted using IBM SPSS Statistics v22 (IBM Cooperation, USA).

### Results

The demographic characteristics of the sample are presented in Table 1, and a summary of VERITAS-BEANZ statistics are presented in Table 2. In total, 529 individual destinations were geolocated (mean =  $17.9 \pm 5.11$ ), with similar numbers between genders. The number of destinations that participants had visited but were unable to locate was 76, although 36.8% of these were from three participants who were unfamiliar with interpreting maps. The time taken to complete the questionnaire averaged  $28.3 \pm 9.4$  minutes, and was significantly correlated with the number of destinations geolocated ( $r = .61$ ,  $p < .01$ ). Overall, 41% of visited destinations were inside the perceived neighbourhood boundary, with females showing a slightly higher percentage than males (44.73 and 38.54%, respectively), although this difference was not significant ( $p = .56$ ). The level of neighbourhood attachment (mean =  $4.39 \pm 1.13$ ) was unrelated to the number of destinations that fell inside the perceived neighbourhood ( $r = .11$ ,  $p = .57$ ) or its area ( $r = -.08$ ,  $p = .70$ ).

Table 3 shows the characteristics of each type of destination. On average, the closest destinations to home were public parks ( $0.89 \pm 0.88$  km), public transit stops ( $1.37 \pm 2.68$  km), schools with recreation facilities ( $1.47 \pm 1.17$  km), and convenience stores ( $1.48 \pm 1.01$  km). These four destinations also had the highest proportion of active transport trips (88.2, 81, 54.5, and 56% respectively). Overall, network distance to destinations was positively associated with passive travel ( $r = .68$ ,  $p < .01$ ), negatively associated with active transport ( $r = -.63$ ,  $p < .01$ ), and negatively associated with traveling alone ( $r = -.46$ ,  $p < .05$ ). The

distance accumulated per year metric shows the relative importance of each destination for each mode of travel (although it assumes trips are made from the principal residence and thus ignores trip chains). Across the whole sample, the most active (457 km), passive (1067 km), and mixed (611 km) transport distance was accumulated during the commute to and from school. Passive transport distance was also high when travelling to organised sport (669 km) and indoor recreation facilities (634 km), whereas active transport distance was high when travelling to playing fields (291 km), public transit stops (257 km), and friends' houses (167 km). Public open spaces and cultural or religious activities also had high active transport distances, although only one third of participants visited these types of destinations. Being allowed to travel to a destination without adult supervision was positively associated with traveling alone ( $r = .61$ ,  $p = .01$ ) and having friends as travel companions ( $r = .64$ ,  $p < .01$ ), but negatively associated with passive travel ( $r = -.50$ ,  $p < .01$ ). Active travel was positively associated with traveling with friends ( $r = .53$ ,  $p < .01$ ), siblings ( $r = .43$ ,  $p < .05$ ) and alone ( $r = .55$ ,  $p < .01$ ), but negatively associated with adults ( $r = -.71$ ,  $p < .01$ ).

Table 4 compares urban form characteristics and geometric features assessed within each neighbourhood delimitation. On average, the perceived neighbourhood boundary area ( $3.54 \pm 2.64$  km<sup>2</sup>) was larger than a NZ meshblock ( $0.12 \pm 0.16$  km<sup>2</sup>) and a 1 km network buffer ( $1.03 \pm 0.33$  km<sup>2</sup>) but smaller than a 1 mile Euclidean buffer ( $8.14 \pm 0$  km<sup>2</sup>). The proportion of area which fell inside the perceived neighbourhood boundary was highest in meshblocks (85.1%) followed by the 1 km network (79.4%) and 1 mile Euclidean buffers (34.6%). The distance to the farthest boundary vertex was considerably longer than the distance to the closest edge, and the ratios between these distances were similar in all neighbourhood delimitations apart from the 1 mile Euclidean buffer (which has perfect shape uniformity). The perceived neighbourhood boundary showed greater circularity ( $0.69 \pm 0.15$ ) than meshblocks ( $0.53 \pm 0.15$ ) and 1 km network buffers ( $0.0 \pm 0.0$ ). The urban form characteristics varied substantially between each neighbourhood delimitation, although residential density and street connectivity were similar between the 1 km network buffer and the perceived neighbourhood.

**Table 1 Participant demographic characteristics (mean  $\pm$  SD)**

	Male n = 14	Female n = 14	All n = 28
Age	15.84 $\pm$ 1.49	15.91 $\pm$ 1.53	15.88 $\pm$ 1.48
Height (cm)	174.24 $\pm$ 7.87	164.55 $\pm$ 4.78	169.40 $\pm$ 8.07
Weight (kg)	61.91 $\pm$ 9.80	57.45 $\pm$ 8.13	59.68 $\pm$ 9.12
BMI	20.33 $\pm$ 2.48	21.17 $\pm$ 2.42	20.75 $\pm$ 2.44
Waist circumference (cm)	72.58 $\pm$ 7.09	67.56 $\pm$ 5.12	70.07 $\pm$ 6.58

### Discussion

Although the built environment has been shown to contribute to young people's activity and health behaviours [3,47], current evidence is inconsistent and exactly how the environment exerts its influence remains largely unclear [45,48]. As such, daily mobility and spatial polygamy have been identified as important elements to further our understanding of the environment-health

**Table 2** VERITAS statistics

	Male n = 14 mean ± SD (min - max)	Female n = 14 mean ± SD (min - max)	All n = 28 mean ± SD
Time to complete VERITAS (min)	30.73 ± 11.61 (13.25 - 64.8)	25.79 ± 6.10 (16.8 - 42.75)	28.26 ± 9.44
Number of destinations geolocated	17.50 ± 5.5 (8-27)	18.29 ± 4.86 (13-29)	17.89 ± 5.11
Destinations inside perceived neighbourhood (%)	38.54 ± 31.18 (0 - 90)	44.73 ± 23.37 (0 - 81)	41.64 ± 27.22
Neighbourhood attachment (1 to 6 scale)	4.21 ± 1.25 (2-6)	4.57 ± 1.02 (2-6)	4.39 ± 1.13
Number of people living at address	4.43 ± 1.16 (3-7)	4.00 ± 1.30 (2-6)	4.21 ± 1.23

relationship [5,10]. The development of electronic activity destination questionnaires which incorporate interactive mapping technologies are thought to allow a more comprehensive assessment of daily mobility and perceived spaces. This study sought to demonstrate VERITAS-BEANZ as an innovative method to assess mobility in adolescents.

Our results indicate that locating destinations of interest on an electronic map were relatively straightforward for the majority of participants regardless of gender and age. The interview technician's local area knowledge proved to be beneficial when helping participants locate destinations, especially individuals who were not accustomed to reading maps. The search tools embedded within VERITAS were useful when participants knew the name of the destination and an approximate location, but were unable to pinpoint the destination itself. It was found that displaying the map using a hybrid view (i.e., a satellite view superimposed with roads and street names) assisted participants in pointing out familiar landmarks (such as treed areas and clusters of buildings) that were not visible on a simple street map (Figure 1).

Table 3 shows that certain destinations feature more regularly within adolescent's daily trajectories (e.g., own school, other schools with recreation facilities, sporting activities) while others afford a higher proportion of active transport trips (e.g., public parks, public transportation services, friends' houses). The identification of common destinations to which adolescents travel is not only relevant for the development of targeted interventions, but because the importance of these destinations may vary for other population groups who are also exposed to that environment. For example, a built environment change might be more suited or have more influence on one population group compared to another, but understanding these relationships can be a methodological challenge. The location-based methodology performed in this study closely resembles the softGIS methodology developed by Kytä and colleagues [49,50] which has led to a better understanding of children's meaningful places from their own perspective. These approaches allow the collection of geographically referenced

'soft' information which takes into consideration the individual's experiential knowledge. When combined with traditional GIS data layers, this type of information has been a welcome addition to evidence-based planning [51,52]. Our results also demonstrate that destinations closer to home (i.e., public parks), have a higher proportion of active transport trips, which is consistent with current literature; distance is one of the strongest predictors of active transportation in young people [53,54]. Being allowed to travel without adult supervision was also associated with greater active travel, alluding to the importance of independent mobility in adolescent populations. Although parental willingness for independent travel is affected by crime and other safety factors [53], parents may be prone to allow greater independent mobility when destinations are closer to home, which translates into greater active travel.

The results presented in Table 4 show the perceived neighbourhood is not uniform in all directions, which highlights the limitation of circular buffers which are derived from fixed radial distances around the home [4]. These data also suggest that the distance from the residence to the edge of the neighbourhood delimitation is not the only variable to consider, but also the shape and positioning of the neighbourhood around the home. Network buffers can somewhat overcome this problem by accounting for environmental barriers and hazards along the street network, yet on average, 20% of the 1 km network buffer area fell outside the perceived neighbourhood. Although the chosen buffer size may have contributed to this discrepancy, network buffers cannot account for destination preferences or the spatial distribution of local resources and amenities around the home, which likely influence the shape of perceived or experienced neighbourhoods. Table 4 also demonstrates that measures of walkability differ between each of the neighbourhood delimitations, suggesting the presence of the modifiable areal unit problem (MAUP); these environmental variables are sensitive to the spatial unit that is applied to the aggregation of these data. It has been demonstrated previously that the association between various environmental attributes and adolescent's physical

**Table 3** Geolocated destination characteristics

Destination	Network distance (km)	Visited (%)	Frequency (times/year)	Mode of travel (%)			Weighted distance (km/year)*			Without adults (%)	Travel companions (%)			
				Active	Passive	Mixed	Active	Passive	Mixed		Friends	Siblings	Parent	Alone
Oven School	4.09 ± 3.84	100	261 ± 10	21.4	50	28.6	456.89	1057.49	610.6	96.4	71.4	42.9	14.3	32.1
Playing Fields & Courts	3.59 ± 5.94	50	81 ± 57	50	50	0	250.79	290.79	0	100	57.1	28.6	42.9	42.9
Public Open Space	9.69 ± 8.47	32.1	32 ± 49	44.4	33.3	22.2	269.67	202.25	134.83	88.9	77.8	44.4	44.4	0
Public Transit Stop	1.37 ± 2.68	75	116 ± 109	81	14.3	4.8	257.45	45.45	15.26	100	57.1	33.3	9.5	57.1
Cultural or Religious	3.58 ± 2.78	35.7	113 ± 111	30	60	10	242.72	485.45	80.91	-	50	20	40	50
Visiting friends	1.76 ± 2.31	82.1	91 ± 70	52.2	26.1	26.1	167.21	83.6	83.6	-	30.4	21.7	26.1	68.2
Beach or Lake	3.63 ± 5.9	75	45 ± 35	47.6	33.3	19	155.51	108.79	62.07	95.2	81	33.3	66.7	33.3
Swimming Pool	6.84 ± 5.87	39.3	42 ± 49	18.2	72.7	9.1	104.57	417.71	52.28	81.8	27.3	45.5	72.7	9.1
Sport	4.93 ± 6.17	82.1	120 ± 68	8.7	56.5	34.8	102.94	668.51	411.75	-	56.5	30.4	52.2	21.7
Indoor Recreation	4.33 ± 4.19	57.1	90 ± 60	12.5	81.3	6.3	97.43	633.65	49.1	81.3	25	18.8	37.5	31.3
Basketball Court	2.41 ± 2.95	26.8	50 ± 37	37.5	50	12.5	90.38	120.5	30.13	87.5	75	62.5	25	25
School with Recreation Facilities	1.47 ± 1.17	39.3	56 ± 52	54.5	36.4	9.1	89.73	59.93	14.98	100	90.9	54.5	0	18.2
Public Park	0.89 ± 0.88	60.7	49 ± 32	88.2	0	11.8	76.93	0	10.29	100	76.5	35.3	29.4	35.3
Convenience Store	1.48 ± 1.01	80.3	47 ± 33	56	28	16	69.62	34.81	19.89	96	48	36	24	48
Any Other School	1.97 ± 1.8	39.3	26 ± 36	50	28.6	21.4	51.72	29.3	21.92	100	64.3	42.9	35.7	35.7
Fast Food	4.17 ± 5	82.1	31 ± 31	17.4	60.9	21.7	44.99	157.45	56.1	82.6	52.2	34.8	65.2	13
Walking Trails	2.29 ± 2.18	32.1	19 ± 33	44.4	55.6	0	38.64	48.38	0	55.6	33.3	55.6	88.9	11.1
Café	4.59 ± 4.41	78.6	24 ± 24	9.1	63.6	27.3	20.05	140.12	60.15	95.5	54.5	31.8	63.6	4.5
Video or DVD Store	2.05 ± 1.29	71.4	32 ± 24	15	40	45	19.68	52.48	59.04	100	55	35	75	25
Supermarket	2.29 ± 1.29	96.4	57 ± 35	7.4	59.3	33.3	19.32	154.81	86.91	92.6	18.5	37	81.5	7.4
Chemist	1.84 ± 1.43	67.9	22 ± 27	21.1	47.4	31.6	17.08	38.38	25.58	63.2	5.3	21.1	89.5	15.8
Bank	2.88 ± 1.52	82.1	18 ± 13	8.7	65.2	21.6	9.02	67.6	22.39	69.6	4.3	13	87	30.4
Restaurant	4.18 ± 4.76	71.4	17 ± 11	5	75	20	7.11	105.59	28.42	65	40	40	95	0
Post Office	2.85 ± 1.94	46.4	11 ± 9	7.7	69.2	23.1	4.83	43.39	14.48	69.2	0	23.1	84.6	15.4
Clothing Store	5.42 ± 3.22	82.1	36 ± 30	0	87	13	0	399.51	50.73	95.7	73.9	30.4	69.6	26.1
Bookstore	4.48 ± 2.82	39.3	30 ± 60	0	81.8	18.2	0	219.88	48.92	100	27.3	27.3	100	18.2
Library	4.39 ± 2.89	64.3	12 ± 8	0	77.8	22.2	0	81.97	23.39	94.4	44.4	16.7	55.6	27.8
Laundry	3.85 ± 0	3.6	1 ± 0	0	100	0	0	7.7	0	0	0	0	100	0

\*Weighted distance = (network distance × 2) × frequency × (mode of travel ÷ 100).

**Table 4 Neighbourhood and activity space geometry and urban form comparison (mean  $\pm$  SD)**

	VERITAS perceived neighbourhood	NZ meshblock	1 mile Euclidian buffer	1 km network buffer	Activity space (convex hull)
Area (km <sup>2</sup> )	3.54 $\pm$ 2.64	0.12 $\pm$ 0.16**	8.14 $\pm$ 0	1.03 $\pm$ 0.33**	19.67 $\pm$ 24.83
Perimeter (km)	7.38 $\pm$ 3.38	1.57 $\pm$ 0.90**	10.11 $\pm$ 0	5.98 $\pm$ 1.45**	19.56 $\pm$ 10.89
Home to farthest boundary edge (km)	2.44 $\pm$ 1.38	0.53 $\pm$ 0.37**	1.61 $\pm$ 0	0.9 $\pm$ 0.09**	6.77 $\pm$ 4.3
Home to closest boundary edge (km)	0.54 $\pm$ 0.39	0.05 $\pm$ 0.04**	1.61 $\pm$ 0	0.18 $\pm$ 0.11**	0.36 $\pm$ 0.31
Farthest to closest edge ratio	10.88 $\pm$ 13.33	14.44 $\pm$ 12.55	1 $\pm$ 0**	13.48 $\pm$ 27.24	26.06 $\pm$ 24.53
Neighbourhood circularity	0.69 $\pm$ 0.15	0.53 $\pm$ 0.15**	1 $\pm$ 0**	0 $\pm$ 0**	0 $\pm$ 0
Perceived neighbourhood overlap (% area) <sup>b</sup>	-	85.12 $\pm$ 27.39	34.64 $\pm$ 21.73	79.43 $\pm$ 27.11	25.16 $\pm$ 23.54
Land Use Mix (entropy score)	0.38 $\pm$ 0.21	0.22 $\pm$ 0.16*	0.47 $\pm$ 0.15*	0.29 $\pm$ 0.12**	0.60 $\pm$ 0.16
Residential Density (dwellings/km <sup>2</sup> )	807.83 $\pm$ 233.75	894.17 $\pm$ 321.34**	627.34 $\pm$ 180.73**	854.29 $\pm$ 199.47	674.31 $\pm$ 189.0
Connectivity (intersections/km <sup>2</sup> )	45.35 $\pm$ 17.93	23.71 $\pm$ 23.7**	59.89 $\pm$ 21.18**	40.99 $\pm$ 7.7	52.01 $\pm$ 11.41

Note: \*Significantly different from VERITAS perceived neighbourhood ( $p < .05$ ).

\*\*Significantly different from VERITAS perceived neighbourhood ( $p < .01$ ).

<sup>b</sup>Calculated as the percentage of each neighbourhood's area that fell inside the perceived neighbourhood boundary.

activity was dependant on weather a 400 m or 1 mile buffer around the home was used as a spatial aggregation unit (i.e. the neighbourhood) [55]. More recently, differences in built environment variables calculated within six different geographic representations of a neighbourhood highlighted the presence of scaling and zoning effects across these different neighbourhood delimitations [56]. It has been suggested that a strong behavioural justification is needed when deciding how the neighbourhood construct is represented spatially [57]. The interaction between an individual and their environment must be taken into account, yet investigators commonly take a 'one spatial definition fits all' approach to defining study subjects neighbourhoods, in which a single neighbourhood definition is applied to all participants regardless of age, gender, location and mobility patterns. A recent study found that adolescent's self-identified neighbourhoods were not significantly different in area from census-defined neighbourhoods, but the self-identified neighbourhoods were shown to better capture environments where adolescents spent their time and engaged in MVPA [36], which suggests perceived spaces may be a better representation of an individual's experienced space.

More than half of all geolocated destinations (58%) were beyond the bounds of the perceived neighbourhood. The reality is many adolescents are not restricted to their neighbourhoods during daily living, and are able to use passive methods of transportation to access destinations far beyond their neighbourhood limits. The perceived neighbourhood delimitation might closely represent areas travelled to on foot; an individual may feel a higher level of attachment to that area as these environments are more likely to be experienced intimately. On average, the perceived neighbourhood represented just over a quarter of the total activity space

area. These factors support the use of activity space measures that account for the full extent of places visited instead of relying solely on restrictive definitions of place (such as the residential neighbourhood) which could lead to incorrect estimates of exposure [5]. Precise measures of exposure allow for a more robust and revised estimate of the true magnitude of association between behavioral and environmental variables. Improving exposure and outcome variable precision may significantly reduce the chances of a type 2 error; reporting there isn't an effect when in reality there is.

#### Limitations and future applications

Although the use of activity spaces have been proposed as a step forward in this field [5], the spatial area within convex activity-space polygons may contain environments to which the individual is not exposed [16]. Buffering individual destinations and routes between these destinations (buffer size dependant on location and mode of travel) may more closely reflect true exposure [18,58]. The development of domain specific activity spaces (e.g., green space or foodscape exposure) [59] or travel mode activity spaces (e.g., active transport activity space) by circumscribing destinations and routes that are associated with that domain, or travelled to by that mode, will help to isolate environmental effects on the variable of interest. Although VERITAS can obtain retrospective data over extended periods, the data is essentially subjective in nature, and lacks the temporal sequence of events that can be obtained from GPS receivers [16]. Thus, the collective use of activity destination questionnaires and GPS receivers is warranted, as they provide complementary information, leading to more accurate estimates of daily mobility and environmental exposure.

## Conclusions

In summary, the use of activity destination questionnaires with integrated mapping components, such as VERITAS-BEANZ, may help to overcome the shortcomings of previous studies, and are a practical and effective means for attaining geographic information for assessing daily mobility and perceived spaces in adolescent groups.

## Competing interests

The authors declare that they have no competing interests.

## Authors' contributions

TS, SD, BC, and YK contributed to the design of VERITAS-BEANZ. TS performed data collection, data analysis, and drafted the manuscript. SD, BC, YK, JS, and GS participated in the critical revision of the manuscript. All authors read and approved the final manuscript.

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## Appendix E. Ethical approval



AUTEC  
SECRETARIAT

11 April 2013

Grant Schofield  
Faculty of Health and Environmental Sciences

Dear Grant

Re: Ethics Application: **12/161 Built environments and physical activity in New Zealand youth.**

Thank you for your request for approval of amendments to your ethics application.

I have approved a minor amendment to your ethics application allowing data collection from a sub-sample group by GPS.

I remind you that as part of the ethics approval process, you are required to submit the following to ATEC:

- A brief annual progress report using form EA2, which is available online through <http://www.aut.ac.nz/researchethics>. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 31 July 2015;
- A brief report on the status of the project using form EA3, which is available online through <http://www.aut.ac.nz/researchethics>. This report is to be submitted either when the approval expires on 31 July 2015 or on completion of the project.

It is a condition of approval that ATEC is notified of any adverse events or if the research does not commence. ATEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

ATEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this. If your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply there.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at [ethics@aut.ac.nz](mailto:ethics@aut.ac.nz).

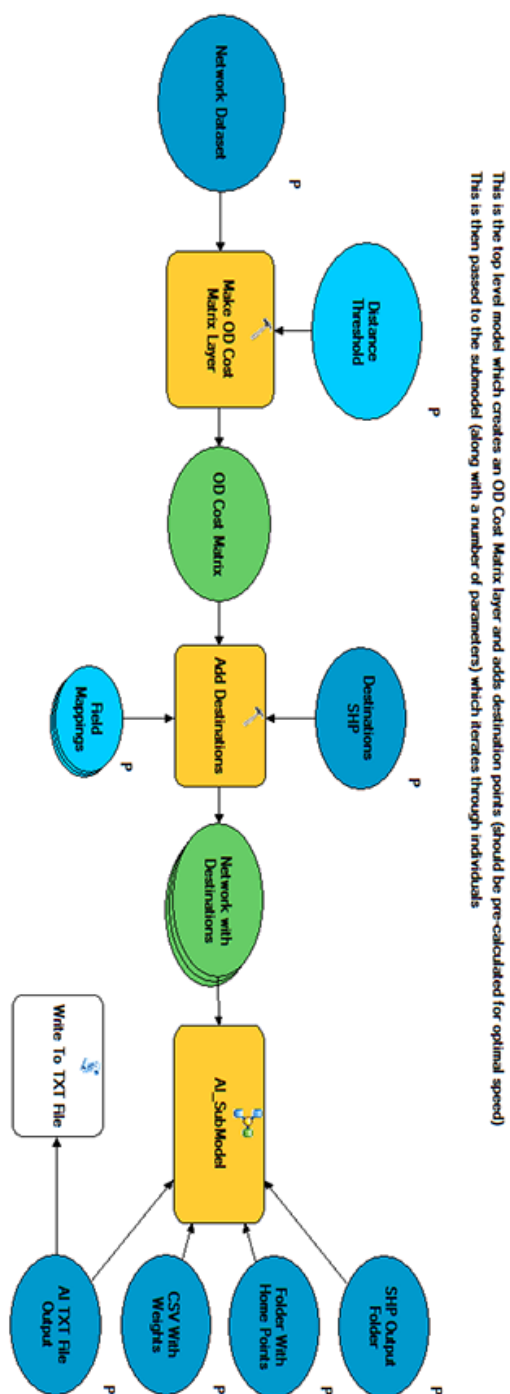
All the very best with your research,

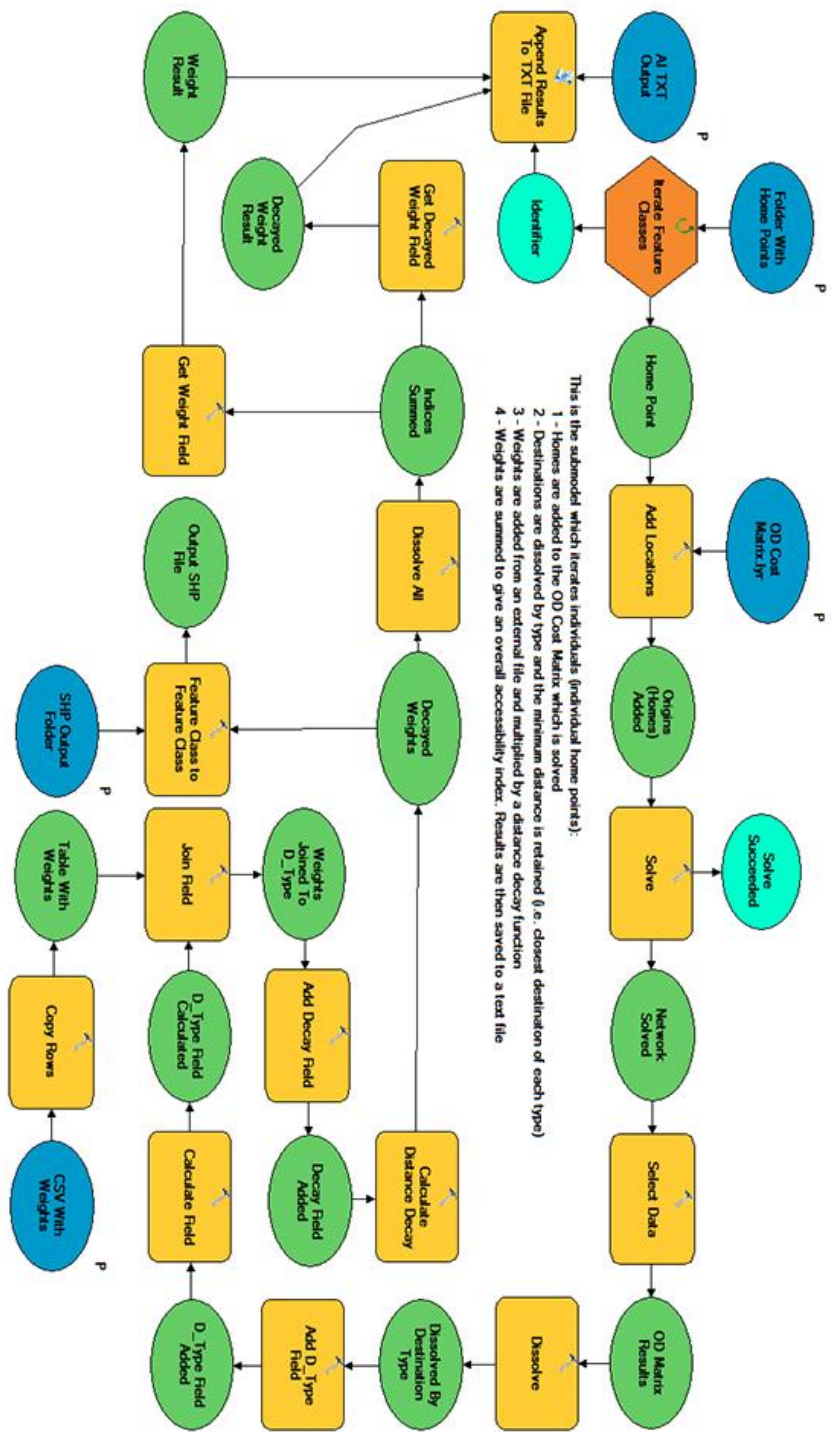
A handwritten signature in dark ink, appearing to read 'Rosemary Godbold'.

Dr Rosemary Godbold  
Executive Secretary  
**Auckland University of Technology Ethics Committee**

Cc: Erica Hinkson; Melody Oliver; Scott Duncan; Julia McPhee; Kate White

## Appendix F. Accessibility index ArcGIS Model Builder workflow





## Appendix G. Equipment information sheets and compliance logs

BEANZ Study

ID:

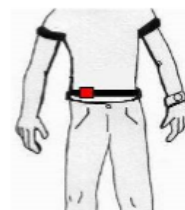
### How to use the accelerometer this week

This small activity meter records general movement and allows us to get a better idea of your overall activity level. We will not be able to tell what kind of specific activity is happening. At first, the belt may feel slightly awkward, but after a few hours, you will probably get used to it and not notice it as much. It is **extremely** important for our study that you wear the meter properly. If it is not worn properly, we may have to send it back for you to wear again. Please follow these instructions carefully:

- Wear the meter attached to the belt around your waist, just above your **right** hipbone. You can wear it either underneath or on top of your clothing.
- Wear the meter so that the star sticker is facing **up**.
- Wear the meter **snug** against your body. If you have to, you can adjust the belt by pulling the end of the strap to make it tighter. Or, to loosen the belt, push more of the strap through the loop. **Wear the belt tight enough so that the meter does not move when you are being active.**
- Please **put it on first thing in the morning** – either just after you get out of bed or just after you shower or take a bath in the morning.
- **Do not submerge the meter in water** (swimming, bathing, etc.)
- Keep the activity meter on all day (unless swimming or in the water).

➤ At night, **take it off right before you go to bed**. You should be wearing the meter for **at least 12 hours each day**.

➤ Do not let anyone else wear it.



We would appreciate it if you could please complete the tables on the following pages. Please try to complete the tables daily, rather than from memory at the end of the week.

Many thanks once again for your interest and participation in the study.

**Please complete the table over the page and return this form to school on Tuesday 22 October**

If you have any questions please don't hesitate to contact Tom Stewart ([tom.stewart@aut.ac.nz](mailto:tom.stewart@aut.ac.nz), 921909 ext 7779)

The expectation is that you will wear your accelerometer throughout your waking time. In the event that you remove your accelerometer please indicate this in the table below. Please complete the table below each day as accurately as you can. Please record your answers using **24 hour time format**.

	e.g.	Day 1: Monday 14 October	Day 2: Tuesday 15 October	Day 3: Wednesday 16 October	Day 4: Thursday 17 October	Day 5: Friday 18 October	Day 6: Saturday 19 October	Day 7: Sunday 20 October	Day 8: Monday 21 October	Day 9: Tuesday 22 October
1. What time did you <b>wake up</b> ?	0700									
2. What time did you <b>attach the accelerometer</b> ?	0700									
3. What time did you <b>remove the accelerometer</b> ?	2130									<b>Return forms today</b>
4. What time did you <b>go to bed</b> ?	2130									
5. What other times during the day was the <b>accelerometer not worn</b> ?	1100-1130									
6. What were you doing when you were not wearing the accelerometer	Swimming									

If you have any questions please don't hesitate to contact Tom Stewart ([tom.stewart@aut.ac.nz](mailto:tom.stewart@aut.ac.nz) 921999 ext 7779)

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Protocol for equipment safety

Dear Student,

Thank you for taking part in this study. As the researcher has explained, you are required to wear an accelerometer and a GPS receiver for 7 days. Both of these devices should be worn when you are awake and they can be removed when you go to sleep at night. These devices are NOT waterproof and should be removed when showering, bathing or swimming.

AUT adopts a 'safety first' principle, which means unconditional priority of your safety over scientific objectives. Missing GPS or accelerometer data is always preferred to any accident, injury or loss/damage of equipment. This means you may remove the accelerometer and/or GPS receiver at any time should you experience any discomfort or irritation while wearing the equipment. All information recorded from the devices is not linked to a person but to a unique identifier code, to protect participant privacy.

The accelerometer is a small device worn around your waist on an elastic belt. The devices are setup by the researchers prior to distribution, and therefore require no interaction or input from you during the course of the study. The GPS unit will be worn inside a small pouch on the same elastic waist belt as the accelerometer. Due to the battery life of GPS receivers, you will need to plug in the receiver each night before you go to sleep. This is done by turning off the receiver and using the charging cable provided.

Each morning when you wake up you should unplug the GPS receiver from the charger and turn it on. This is done by sliding the button on the side of the receiver to the 'LOG' setting. Do not slide the button to the 'NAV' setting or it will not work.



The main points you need to remember are:

- Wear both devices during the day when you are awake.
- Remove them when showering, bathing or swimming.
- Charge the GPS receiver each night when you go to sleep.
- Make sure the GPS receiver is set to the LOG setting when you turn it on each morning.
- You may remove the devices at any time if you experience any discomfort.

If you have any questions about the equipment please do not hesitate to contact the researcher.

(email: [tom.stewart@aut.ac.nz](mailto:tom.stewart@aut.ac.nz))

Monday 10th June

In the event that you remove your GPS please indicate this in the table below. Please complete the table below each day as accurately as you can.

Please record you answers using **24 hour time format**.

	e.g.	Day 1: Monday 26 August	Day 2: Tuesday 27 August	Day 3: Wednesday 28 August	Day 4: Thursday 29 August	Day 5: Friday 30 August	Day 6: Saturday 31 August	Day 7: Sunday 1 September	Day 8: Monday 2 September	Day 9: Tuesday 3 September
1. What time did you attach the GPS?	0700									
2. What time did you remove the GPS?	2130									Return forms today
3. What other times during the day was the GPS not worn?	1100-1130									
4. What were you doing when you were not wearing the GPS	Swimming									