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Human Healthscapes as an Approach to Measuring Context in Research on Place and Health

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Human Healthscapes as an Approach to Measuring Context in Research on Place and Health

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Thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
in partial fulfillment of the requirements for the
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Ph.D. in Population Health Program
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Human beings require both space and place.

Human lives are a dialectical movement between shelter and venture, attachment and freedom.

A healthy being welcomes constraint and freedom, the boundedness of place and the exposure of space. (p 54)

Yi-Fu Tuan, 1977.
Space and Place: The Perspective of Experience
University of Minnesota Press

Abstract

To study how context influences health and well-being it is first necessary to measure the boundary of a person's geographical context. Rigorous description of context is difficult and existing studies have offered weak and mixed evidence about the importance of context to health. Either the characteristics of places have been inadequately conceptualized, or the spatial definition of place relies on inflexible administrative boundaries and a limited set of corresponding attribute data. Furthermore, the influence of context on health presumably depends a great deal on the amount of time spent in each space, and the potential for misclassifying context is greater for individuals whose routine activities are spatially diffuse. However, errors in spatial classification are usually not specified in studies linking context to health.

This dissertation combines theories from geomatics and population health to argue that the time geography of human activities has an important role in delineating and describing contexts relevant to health. Specifically, the contextual impact on health status reflects not only the person's immediate neighbourhood, but also locations where other activities of daily life occur. The theoretical contribution of the thesis is to conceptualize context as a healthscape — a spatial notion that captures an array of contexts defined by individuals as they navigate through the spatial patterns of daily life. The empirical goal of the dissertation is to compare these healthscapes to contexts delineated by census tract geographies typically used in health and place research.

Individual healthscapes are defined by developing a wearable global positioning system and data logger that records an individual's location and

velocity at one-second intervals over a seven-day period. Data from 53 people are linked to responses from a health questionnaire. Several approaches drawn from ecology and spatial statistics are used to quantify the properties of each person's spatial activity patterns, or healthscape. These objectively measured contexts are compared statistically to the traditionally used census boundaries to examine differences in morphology, compositional and contextual characteristics. The results are broadly consistent with the theoretical justification proposed for healthscapes, and signal the need for place and health research to better represent the geography of human activities.

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This study was funded through multiple sources. I received a three-year Doctoral Research Award from the Canadian Institutes of Health Research, and an Excellence Scholarship from the University of Ottawa. Additional financial support was provided by the McLaughlin Centre for Population Health Risk Assessment, and by Mike Sawada who had the vision to support the development of the wearable GPS data loggers. Environmental Programs at Dalhousie University provided in kind support. Brian Liekens and Mark LeBlanc from Engineering and Gavin King from Environmental Science at Dalhousie University played major roles in the development and piloting of wearable GPS. Jennifer Strang, Raymond Jahncke and James Boxall from the

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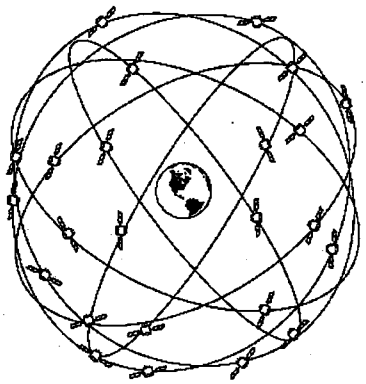
List of Abbreviations

CEP	Circular Error Probable
CI	Confidence Interval
DGPS	Differential Global Positioning System
DOP	Dilution of Precision
GIS	Geographic Information System
GPS	Global Positioning System
HDOP	Horizontal Dilution of Position
KDE	Kernel Density Estimation
LAT	Location-Aware Technology
MCP	Minimum Convex Polygon
MST	Minimum Spanning Trees
NAD	North American Datum
OR	Odds Ratio
PDOP	Positional Dilution of Position
SARS	Severe Acute Respiratory Syndrome
SD	Standard Deviation
SDE	Standard Deviational Ellipse
UTM	Universal Transverse Mercator

Chapter 1

Introduction



Statement of the Problem

Over the past few decades, the focus of understanding variations in the determinants of health has shifted from a concentration on the individual to include the influence of place. In the shift towards an emphasis on place, differences in health status unaccounted for by the compositional characteristics of the individual, such as personal lifestyle and behavioral characteristics, are attributed to characteristics of an individual's environment or context (Arcury et al., 2005; Boyle and Willms, 1999; Curtis and Jones, 1998; Macintyre et al., 2002; Tunstall et al., 2004). Two workshops on place and health, sponsored by the Canadian Institute of Health Information, have highlighted two fundamental issues in contextual health research: 1) theoretical contributions to place and health research tend to be a-spatial, and 2) the operationalization of place as represented by administrative boundaries is often imprecise and reflects poorly the experience of people who live within them (CIHI, 2003; CIHI, 2005). Empirical knowledge of the relationships between contexts and health is particularly important in order to deliver effective, 'contextually-sensitive' population health policy interventions (Burrows and Bradshaw, 2001; Macintyre et al., 1993; Smolensky, 1973).

For the majority of studies of context and health, described by Cummins et al. (2007) as 'conventional' place and health studies, there is a prevailing approach in which a theory of how place affects health is fashioned and then explored by geocoding the residential locations of the population under study to one or more spatial units, usually census tracts, wards, or other 'neighbourhood' level equivalents. Place of residence is adopted as the origin for spatial boundary selection and the characteristics of the geography chosen, or

of the people who live within it, are surrogates for context. There are a few good reasons for conducting place and health research in this manner and the approach has led to the development of advanced quantitative methods and multilevel techniques for modeling of a general context effect (Chaix et al., 2005; Diez Roux, 2001; Sampson, 2003). A review of 25 multilevel studies found that 23 reported a statistically significant association between at least one 'neighbourhood' measure of socioeconomic status and health, after controlling for individual socioeconomic status (Pickett and Pearl, 2001). However, it was also noted that

> investigations of the role of neighbourhood level [small area] social factors on health are characteristic of preliminary, exploratory studies in epidemiology. Certain aspects of study design are in need of improvement before the field can advance...and point the way toward more sophisticated studies of societal determinants of health (pp 120-121).

Despite appeals for improvements in study design, most notably in the operationalization of context, a recent review of 86 studies of context and health published since 1998 found that the majority employed administrative or statistical spatial units to define context, despite their lack of intrinsic meaning in relation to health (Riva et al., 2007).

The current approach to operationalizing context in health research appears fixated on pivotal assumptions about the spatial geometry of analysis. A behavioural strategy rooted in the notion of agency focuses on the development of empirically valid statements about individual behaviours and routines that can be used to develop a more objective spatial structure of context. The notion of *healthscape* as an evolution of Gesler's 'therapeutic landscapes' (1992), represents an opportunity to operationalize context as expressed though human agency and the spatial and temporal activities of daily

life. In practice, healthscapes are developed using approaches drawn from spatial statistics and computational geometry, and can be used to explore the boundaries of context theorized to influence health, the characteristics of social networks, as well as the spaces within which activities occur. The relationship between the healthscape and the determinants of health works reciprocally to influence variations in health status and well-being.

Compared to conventional context and health approaches, the healthscapes approach to health views context as a reciprocal product of human activities. An integral aspect of the healthscape perspective is the inclusion of human agency. One of the first conscious attempts to describe the interaction between individual action and context was Geddes (1949) formula for the life-process expressed in terms of place, work and folk. This can be expressed as: 'place makes the individual' and the 'individual makes the place'. Human activities produce context which in turn constrains or cultivates opportunities for health. In particular, this perspective includes information about how individuals position themselves in a variety of contexts at specific points in time.

If examined through the lens of time-geography, the geographic differences noted in population health research result from a fundamental dialectic between individual and society, or the interplay among individual agency, interactions among people, and the more structural relationships occurring between people and context. Thrift (1983) noted that to appreciate contextuality is to recapture the flow of human agency as a series of situated events in space and time. Thus, places are produced and maintained by the activities of 'actors' who are either elements of, or are associated with, a

particular place, and who operate individually or in concert across a wide range of geographical scales (Conradson, 2005). These are the ingredients to the development of the healthscape. The healthscapes approach focuses on the ways in which the contextual elements of society manifest in the concrete, day-to-day lives of people and their activities in the production of health. Research is needed to explore how a healthscape approach can be implemented in context and health research. Furthermore, healthscape and conventional approaches should be compared in an empirical manner, not only to identify the geographical patterning of health determinants and outcomes, but also to reveal how the characteristics of these contexts influence health.

In Canada, several research groups have made substantive contributions to the important topic of context in the field of population health. Recently a special issue on the topic of place and health of the *Canadian Journal of Public Health* published seven articles dealing with conceptual issues such as the interpretation of place effects, definitions of neighbourhoods, boundary delineation, scalar effects – all of which widen the population health lens from the characteristics of people to the characteristics of places (Patychuk, 2007). Yet, little is known about the role of human action and agency in shaping context and how these activities can be of use in identifying the contexts relevant to health status (Arcury et al., 2005; CIHI, 2005; Cummins et al., 2007; Matthews et al., 2005; Oakes, 2006).

Purpose

The purpose of this dissertation is to conduct an exploratory study of the degree to which objectively measured individual space-time activity data could

be used to generate and operationalize spatial boundaries for context and health research. Specifically, the research objectives are to:

1. Explore the theoretical dimensions of a healthscapes approach to place and health research.
2. Design, construct and evaluate technology for the capture of individual space-time activity data.
3. Compute and quantify healthscapes for context and health research and compare empirically these geographies with conventional geographies.

The major question under investigation, therefore, is how to use information about individual space-time activities, in conjunction with other dimensions of the environment, to generate a more informed understanding of the context(s) involved in the production of health.

The importance of these objectives is twofold. First, because of its hypothesized influence on the geographic patterning of health, and its role in the structuring of social processes related to health, a contextual approach should be a central component in the design of healthy public policy aimed at equitable improvements in health status. Reducing health inequalities and implementing healthy public policy have been identified as consistent with Canadian values and an imperative to the cohesiveness of community and society (Health Disparities Task Group, 2004). Second, this research will make a contribution to research on the spatiality of health. Population health research has been criticized for inattentiveness towards spatial or dynamic processes (Hayes et al., 1994; Hayes, 2003), while context and health research has been challenged to incorporate the influence of how human agency

translates into individual activities with spatial and temporal properties relevant to health (Gatrell, 1997; Jones and Moon, 1993; Matthews et al., 2005). Research on the association between health and context is moving beyond the identification of geographical differences in health status, towards a more serious engagement of the relational processes showing that contexts are produced and maintained by the activities of individuals and actors who are associated with a particular location. This research contributes to the discourse of these relational processes in context and health research.

Healthscapes and Health: Support for a Conceptual Framework

Individual activities, which occur in particular locations at specific times, have obvious physical or emotional elements that would be expected to influence health. For example, the acts of eating or procuring food, exercising in the park, or conducting work-related activities, are important for well-being and biological functioning. The application of time-geographical concepts to exploring the components of context relevant to the production of health is the subject to be addressed in this thesis.

Figure 1.1 shows the conceptual framework employed in this thesis as the foundation of an alternative, healthscapes approach to conceptualizing contextual influences on health. In this section the components of the figure are introduced and expanded upon by introducing relevant literature. A more expanded and thorough examination of the framework and its application to context and health research is found in Chapter 2.

Along the top of the figure appear the determinants of population health and a few of the predominant bodies of research arising from population health

research literature. The population health approach has been defined as the systematic patterns in the occurrence of interrelated conditions and factors that influence health (Health Canada, 1994; Krewski et al., 2007). The approach explores the health *of* populations using a dynamic view of health and involves the idea of human agency as a catalyst for exploring both emergent conceptions of population health as well as upstream health determinants (McDowell et al., 2004). The focus of population health research has traditionally been to examine why some populations are healthier than others, usually through identification of geographical differences in health status. A contribution of this thesis is to advance the notion that health differences and behaviours are not merely a function of geographic structure but also a function of the context (Jones & Moon, 1993). Income inequalities, social support and health, and lifecourse perspectives are major bodies of research that have contributed to the development of the population health perspective. The latter concerns the cumulative impact of social influences on health outcomes over the course of one's life. Arrows pointing downward indicate the influence of health determinants on individual perceived control, as well as directly on the characteristics of the healthscape.

Theories from psychology help to emphasize individual differences and behaviour changes associated with decision making processes. The theory of planned behaviour, based on traditional social psychology, suggests perceived control as a dominant factor in decision processes (Ajzen, 2002). Perceived control comprises two components: self-efficacy (a person's sense of the ease or difficulty of performing a behaviour) and controllability (level of human agency).

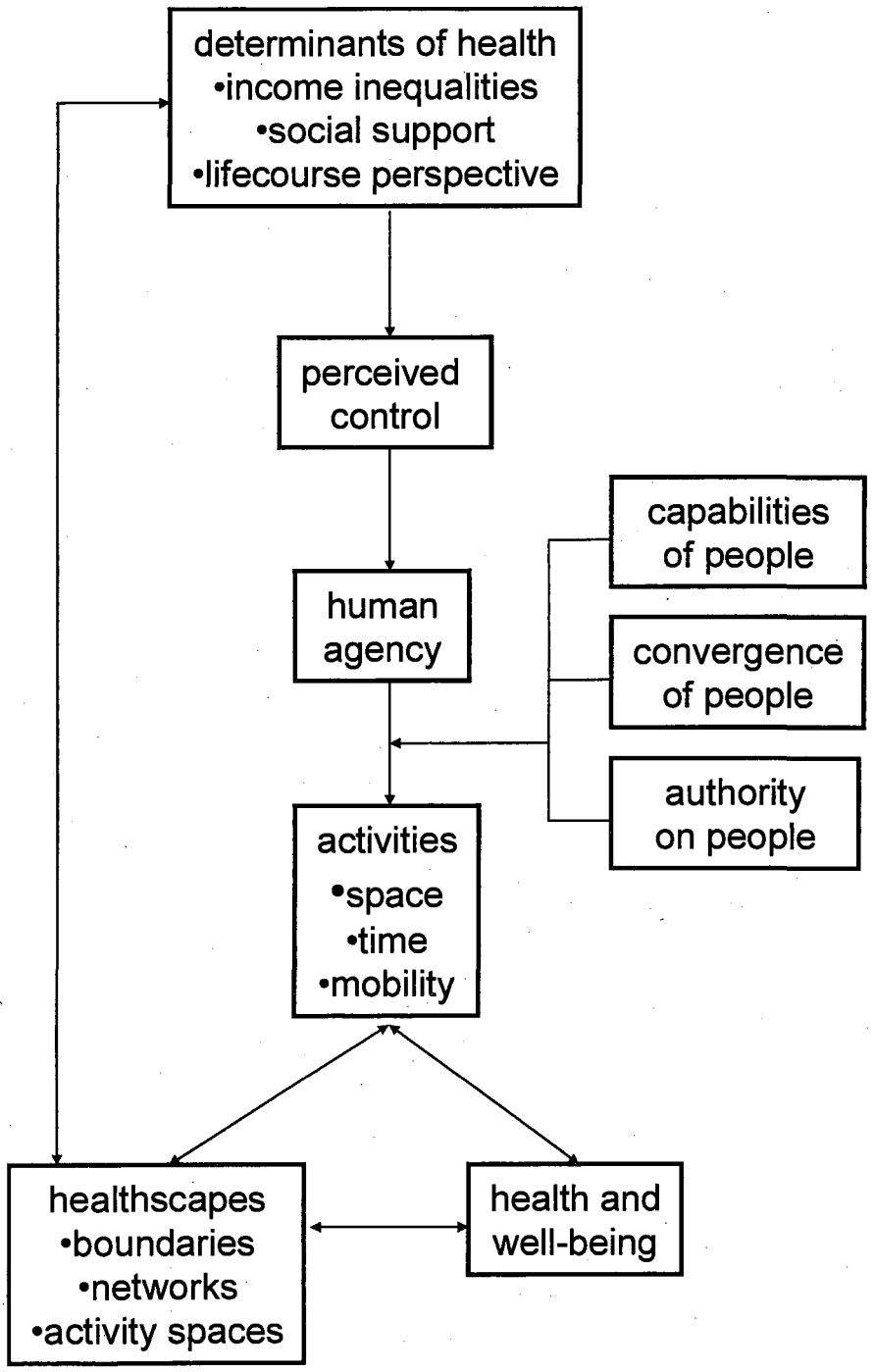


Figure 1.1. A conceptual framework for healthscapes and population health.

It has been shown to account significantly for the intentions and actions of individuals, also known as human agency. While perceived control is influenced by the determinants of health, it is also shaped by individual beliefs about the likelihood that one has the necessary resources and opportunities to perform the behaviour (Eagly and Chaiken, 1998).

Central to the discipline of population health is the study of human-environment relations, and this is also the case for humanistic perspectives in geography. According to Tuan (1976), the humanistic perspective in geography

> is concerned with an understanding of the human world by studying people's relations with nature, their geographical behaviour as well as their feelings and ideas in regard to space and place (p 266).

In the humanist approach human agency is appreciated in its context as a series of situated events in space and time. A humanistic perspective makes two contributions to understanding the role of human agency in context. First, the approach recognizes agency as a continuous expression of social and economic relations that vary according to context. Interestingly, it is context that links individual circumstances to population-level differences. For example, it has been suggested that the collective experience of great events in history (wars, economic depression, plagues) socializes individuals and shapes the formation of personality (Thrift, 1983). Second, humanist perspectives are integrated within Gesler's idea of the therapeutic landscape (1992), or how health and healing processes evolve in specific settings or places. In this thesis the notion of a therapeutic landscape is translated into a process by which human activities create and are created by the healthscape. Individual agency makes a difference to place, and place makes a difference to health.

Three dimensions of human agency, shown in the framework as capability, convergence and authority, act as crucial mechanisms in shaping the activities of individuals. These mechanisms form the nexus of the time-geographic approach which describes a reality where all human activities have spatial and temporal attributes; activities occur in specific places for limited durations (Hägerstrand, 1970; Pred, 1977). The capability of individuals to pursue any activity is influenced by physical and social conditions, genetic predisposition or the latitude to acquire and control resources for personal gain. These activities may coincide in space and time with other people, tools or resources, leading to variations in levels of social interaction or support. However, human agency can be restricted territorially by forces asserting influence and control over geographic areas. The culmination of these forces leads to the structuring of context and invariably the processes leading to the social structuring of society (Parkes and Thrift, 1980; Pred, 1983). These are themes common to both population health research and health geography, and the use of Hägerstrand's time-geographic concept has excellent potential for contributing to an improved explanation of how context influences health status; this thesis adopts a time-geographic approach to investigate how human agency is translated into activities with spatial and temporal properties, which essentially help to identify the contexts relevant to health.

The approach offered by time-geographic concepts, coupled with recent advances geomatics and the ability to develop and model detailed micro-level data, makes it feasible to measure human activity patterns in space and time at individual and aggregate levels. This thesis is novel in this regard as very few, if any, studies have incorporated activity patterns in the exploration of how

context is related to health status and behaviours. To date, multiple spatial concepts have been developed based on the time-geographic approach to describe and operationalize contexts useful for population health research. Example concepts include the space-time path/prism (Kim and Kwan, 2003), potential path area (Kwan, 1998; Miller, 2001), activity space ellipse or circles (Schönfelder and Axhausen, 2004), minimum convex polygons (Buliung and Kanaroglou, 2006), and polygons generated from spatial intensity procedures such as kernel density estimation (Silverman, 1986).

This thesis makes a conceptual contribution to the ongoing development of a relational perspective in place and health research. It argues that aspects of human agency are measurable through the lens of a time-geographic approach, and that these measures will provide a valuable contribution to current issues in context and health, specifically around the problems of integrating agency into a methodology through which context can be defined (CIHI, 2005; Diez Roux, 2004).

This dissertation investigates empirically how the contextual features of society are linked to individual activity patterns and health status, and in so doing, proposes a novel approach to exploring the contextual production of health. Its contribution is primarily methodological. Specifically, the thesis integrates theory and technology in the development of an approach to investigate, in concrete terms, how features of human agency can be measured and integrated into a framework for investigating the relationships between context and health. This thesis also makes a contribution to population health and health geography, by demonstrating the ways in which context as defined

by the routine activities of people is useful to understanding the influence of context on health status.

Organization of the Thesis

This thesis contains six chapters, presented as a series of stand-alone papers formatted for publication comprising Chapters 2, 3 and 4. Chapter 2 situates this research within the discipline of health geography, identifying the application of a time-geographical approach to current issues in the context and health research area. The conceptual piece identifies several issues associated with current methods and proposes the use of human space-time activity information to investigate the differential distribution of context on health status. A thorough understanding of the contexts relevant to health requires accurate and complete information on individual space-time locations over a representative period of time, which has been difficult to measure due to technological limitations.

The second paper, in Chapter 3, attempts to fill this gap, and in doing so results in the development and testing of a novel wearable global positioning system data logger. The chapter provides an overview of GPS and location-aware technologies and identifies past research where GPS has been used in to investigate health issues. It also establishes a general framework of dynamic and static tests for evaluating and testing human tracking devices based on GPS technology.

Chapter 4 presents an empirical cross-sectional study of a random adult sample with application of the wearable GPS devices to develop and operationalize individual healthscapes. GPS data are supplemented with survey

data to test the following null hypotheses: 1) healthscape geography derived from the GPS data will be similar in morphology to census geography typically used in context and health research; 2) health determinants are unrelated to characteristics of the healthscape; 3) there is little to no correspondence between contextual and integral measures using conventional and healthscape geographies; and 4) contextual measures derived from healthscape geographies explain equal variation in health status to individual health determinants and measures using conventional geographies.

The fifth chapter provides a global discussion and conclusion and integrates the findings from the three papers by elaborating on their contribution to the fields of population health and health geography. Chapter 6 contains an overview of the contributions of collaborators. The references for Chapters 1, 5, and 6 and relevant appendices appear in Chapter 7.

Chapter 2

Conceptualizing the Healthscape: Contributions of Time Geography, Location Technologies and Spatial Ecology to Place and Health Research

Rainham, D., McDowell, I., Krewski, D., Sawada, M.

Note: Formatted for the journal Social Science & Medicine.

What is already known on this topic?

- The contextual characteristics of places are associated with health status and health-related behaviours.
- The characteristics of context are in general inadequately conceptualized and operationalized.
- Multidimensional and relational frameworks suggest viable paths for strengthening empirical studies of context and health.

What this study adds:

- The empirical potential of time geography can expand descriptors of context and provide a more rich and meaningful insight of how place affects population health.
- Location-aware technologies, such as global positioning systems and geographic information systems, and related tools in health geomatics, provide the means of deriving the data necessary to conceptualize and operationalize the spatial and temporal characteristics of context.
- The contexts most relevant to health can be expressed as the healthscape, the unique context ascribed to an individual as expressed through the temporal and spatial activities of daily life.

Abstract

Geomatics and related technologies allow for the application of integrated approaches to the analysis of individual spatial and temporal activities in the context of place and health research. The ability to track individuals as they make decisions and negotiate space may provide a fundamental advance beyond conventional place-based perspectives in health research, and invokes the theoretical contributions of time geography and spatial ecology as opportunities to integrate human agency into contextual models of health. Issues around the geographical representation of place are reviewed, and the concept of the healthscape is introduced as an approach to operationalizing context as expressed by the spatial and temporal activities of individuals. We also discuss how these concepts have the opportunity to influence and contribute to empirical place and health research.

Introduction

The study of place and health has been evolving, shaped by an assortment of academic traditions, and this has led to a variety of approaches and considerable debate over the conceptualization and measurement of contextual effects of place on health (Dear & Wolch, 1987; Ellaway, Macintyre & Kearns, 2001; Kawachi & Berkman, 2003; Northridge, Sclar & Biswas, 2003; Pickett & Pearl, 2001). The chief value of place-based research is that it provides the conceptual and analytic platform for studying population health inequalities (Bernard, Charafeddine, Frohlich, Daniel, Kestens & Potvin, 2007; Bottero & Prandy, 2003; Curtis & Jones, 1998; Graham, 2000). The challenge is to recognize when place is the active ingredient in health inequalities, rather than merely a convenient way of describing population groups of different health status. A fuller understanding of how place affects health and healthy behaviours requires information about how the structuring of social processes among people is associated with the structuring of contexts they live in (Jones & Moon, 1993; Kearns & Joseph, 1993; Macintyre, Maciver & Sooman, 1993).

The characteristics of context are more influential to health than we realize and there is good empirical evidence showing that place affects health directly, and indirectly, through influence on individual activities and health-related behaviours (Boyle & Willms, 1999; CIHI, 2003; Diez Roux, 2002; Frolich, Potvin, Chabot & Corin, 2001; Macintyre, Ellaway & Cummins, 2002; Popay, Thomas, Williams, Bennett, Gatrell & Bostock, 2003; Sampson, 2003). Inequalities in health are related to the choices people make and the interactions between people and places. People have varying degrees of autonomy when making choices about where to live and work, who they

socialize with, as well as the actions they take to minimize health risks. However, the freedom to make these choices is often illusory because we seldom account for the features of context and their role in the development of human wellbeing. For example, walking as an activity to promote a healthy lifestyle is less attractive in suburban or semi-rural neighbourhoods that are often lacking sidewalks or trails (Berrigan & Troiano, 2002). Often these health promoting or harming features of context go unnoticed. Yet, it is often the interplay between people and place that ultimately influences health and healthy behaviours. In this sense, healthy places are the contexts within which people should be able to realize their aspirations, satisfy their needs, and adapt or modify their environment to avoid health risks (McDowell, Spasoff & Kristjansson, 2004; Sampson, Morenoff & Gannon-Rowley, 2002; Skjaeveland & Garling, 1997).

Advancing research of context and health relationships requires a re-orientation of the meaning of place. In conventional population health research, geography is ostensibly the spatial container used to differentiate people for the purpose of developing explanations of health and health-related behaviours. The challenge posed by Eyles (1993), and more recently Cummins and colleagues (2007), is to embrace a relational perspective in which context is implicated in human activity. In other words, population health research should be explicitly engaging the spatiality of social life within research on place-based explanations of health. These explanations should recognize that people *and* places make a difference. The separation of people from the places they live in is unhelpful to the development of policy responses to place-based variations in health (Macintyre et al., 2002). While place may potentiate health or sickness, the empirical evidence on what features of place that matter for

health is relatively weak (Diez Roux, 2004; Messer, 2007; Pickett & Pearl, 2001). There are some general and some more specific features. For example, increased incidence of myocardial infarction may have little to do with the walkability of neighbourhoods in a warzone. But if a child is suddenly diagnosed with asthma on moving to a new house or neighbourhood, a specific environmental factor may be implicated.

Advances toward the discovery of contextual features relevant to health have been made in several areas. Qualitative approaches have been used to explore the role of collective lifestyles and social structures as an explanation for variations in neighbourhood-level smoking prevalence (Frohlich, Potvin, Chabot & Corin, 2002), contextual explanations of health inequalities (Popay et al., 2003), as well as relationships between neighbourhood levels of social connectedness and individual health (Frohlich et al., 2002; Popay et al., 2003; Walker & Hiller, 2007). A research focus on the development of place-based health determinants has provided the input for the creation of community contextual health profiles, in some cases for exploring neighbourhood-level variations in specific health outcomes such as cardiovascular disease (Hillemeier, Lynch, Harper & Casper, 2003; Mujahid, Diez Roux, Morenoff & Raghunathan, 2007). Major advances have also occurred in the development and application of alternative spatial structures to analyze context and health associations (Cockings & Martin, 2005; Flowerdrew, Feng & Manley, 2007; Flowerdrew, Manley & Sabel, 2008; Martin, 1998; Ross, Tremblay & Graham, 2004). Despite these advances in contextual health research, place boundaries are usually rigid and disregard temporal processes across geographic space. Many alternatives to conventional spatial structures fall short of integrating the

dynamic character of social life, or the potential for influence from places beyond the 'boundaries' of everyday existence (Sampson, 2003; Wellman & Berkowitz, 1997). This conventional thinking may be less valid in a reality where people and activities are becoming disconnected from locations, and where interactions among people in multiple places are important.

Advancing our understanding of contextual influences on health will require research that transcends emphasis on the structural arrangement of context to a perspective concerned with how people, and the activities they perform, are situated in different contexts at discrete times. But before we can achieve this, we need to decide which contexts to associate with each person. The assignment of a person to place in terms of their home or work address is convenient, but arbitrary and quite inadequate to represent the complexity of the impact of place on health. In addition we need to incorporate time into place research: a space-time metric. In effect, it would be extremely rare for a person to be affiliated with a single spatial unit or structure.

This paper contributes to the conceptual and methodological knowledge of integrating the space-time dynamics of human enterprise into place and health research. A primary focus is on the benefits that accrue from better knowledge of the dynamics of human movement, and how these movements lead to health and place research that acknowledges interactions among people with different health states in multiple contexts. The aim is to supplement conventional ideas of place through a discussion of issues associated with spatial bounding and the role of time geography in place and health, and to review advances in data collection and analysis techniques so that movement and mobility are considered in empirical analyses.

Issues of Spatial Bounding in Place and Health Research

The notion of place varies considerably among studies. It is usually represented in terms of notional geographic boundaries, as implied by 'community', 'neighbourhood', 'meaningful areas', or by terms (census tracts, wards, health regions, counties, postal delivery areas, or zones). The latter define administrative or statistical boundaries developed by government agencies for purposes other than health research, or developed by health researchers employing a variety of statistical procedures. In each of these, place is static, and analyses are constrained by the implicit theoretical perspectives adopted by national and sub-national statistical agencies, as well as practical matters related to data collection. For example, census tracts and block groups as defined by Statistics Canada (Canada's national statistical agency) were originally developed to be relatively homogenous with respect to population characteristics, economic status, and living conditions (Mendelson, 2001). In some instances, such representations of population distribution and context are adequate representations for place and health research. This approach may work well for a traditionally low mobility population living in an area with stable living conditions. In reality, however, neither the people living in an area, nor its attributes, are likely to be static. Data collected by government agencies for the development of public policy are rarely collected with distinct consideration of spatial or dynamic processes (Hayes, 2003). Hence, demographic and census-based variables commonly used in place-based health research form crude markers for the full range of conditions that could buffer or enhance the effects of place on health (Bronfenbrenner, 1977; CIHI, 2003; Gatrell, 2002).

Conventional approaches to delineating boundaries effectively negate the concept of dynamic populations. Attribution of one address or residential boundary as an identifier of the primary place in which health behaviours or outcomes develop may not provide an accurate view of the impact of place. While it could be argued that residential locations or neighbourhoods are distinguished by a stronger sense of attachment to place, most people experience a multiplicity of places and locations. These include work, places to socialize (Allison, Crawford, Leone, Trickett, Perez-Febles, Burton et al., 1999), and 'third places' such as cafés, post offices, and public parks, where people gather and interact. Third places are the necessary ingredients for developing strong community ties and civic engagement (Oldenburg, 2000).

While the diversity of approaches to boundary identification may hinder comparability of results across studies, efforts to more accurately render the boundaries of place will inevitably be more meaningful to the population(s) under study and to the development of place-based health policy. Local knowledge is an effective source of information for identifying neighbourhood boundaries and mapping relationships between context and health (Bernard et al., 2007; Coulton, Korbin, Chan & Su, 2001; Ellaway et al., 2001; Frohlich et al., 2002). This is especially true in more stigmatized neighbourhoods where perceived neighbourhood boundaries can be controversial (Flowerdrew et al., 2007). Several studies have successfully defined places according to boundaries and community assets as perceived and defined by their inhabitants (Coulton et al., 2001; Guest & Lee, 1984; Haney & Knowles, 1978; Lee & Campbell, 1997). Alternatively, researchers have employed statistical-based zone design techniques to explore how altering boundaries can influence the amount of

heterogeneity among spatial units, and hence, research conclusions (Cockings & Martin, 2005; Flowerdrew et al., 2008; Haynes, Daras, Reading & Jones, 2007; Martin, 1998).

Although the ideal level of spatial aggregation for best approximating place remains elusive, researchers should be cautious of results from studies that allocate people to a single context. A recent study on the association between accessibility to green spaces and physical activity allocated the percentage of green space available to an individual within a 1 km or 3 km radius around their home postal code (Maas, Verheij, Spreeuwenberg & Groenewegen, 2008). There are several issues with describing context in this way. First, the choice of distance seems arbitrary. Second, such analyses make no reference to the actual mechanisms linking place to health. Several authors have called for such a theoretical grounding (Diez Roux, 2004; Diez-Roux, 2000; Macintyre et al., 2002). Results are based on the assumption that human activities, as well as the features of place producing health variations among the population of interest, are positioned within a predetermined geographic boundary. Inevitably, this assumption will lead to the misclassification of individuals to the actual context (Diez Roux, 2001), or will severely underestimate the variation in context associated with the heath outcome(s) of interest. Currently there is much uncertainty about appropriate geographic boundaries for place and whether some boundaries are more or less predictive of specific health outcomes (Diez Roux, 2004; Krieger, 2003; Krieger, Chen, Waterman, Soobader, Subramanian & Carson, 2002). Third, in addition to spatial misclassification, place-based health research is subject to the effects of spatial-temporal lag, or the distortion of place and health relationships due to

the passage of time (Schaerstrom, 1999). It seems reasonable to hypothesize that the majority of people do not spend all, or even most of their time in any one pre-defined geographic boundary. An imperative for place and health research is to consider empirically the diversity of places that influence health, including those places geographically distant in space and time. In an increasingly mobile society it would seem valuable to explore the possibility of latency periods between exposures arising from context and the onset of a health condition.

Another important issue in boundary definition is that results are usually dependent on the scale of analysis, which can influence inference (Dungan, Perry, Dale, Legendre, Citron-Pousty, Fortin et al., 2002; Jelinski & Wu, 1996). This concern, also known as the modifiable areal unit problem or MAUP (Gehlke & Biehl, 1934), has two main features. First, analytical differences may arise when results are dependent on the size of the areal units in use (Abrahamowicz, du Berger, Krewski, Burnett, Bartlett, Tamblyn et al., 2004; Geronimus & Bound, 1998; Krieger et al., 2002). The correlation between variables tends to increase with larger geographic boundaries. Second, any effect estimates between place and health will depend to some degree on how the geographic area under study is partitioned, even if analyses are performed at the same scale (Krieger, Waterman, Chen, Soobader, Subramanian & Carson, 2002; Openshaw, 1984). Several solutions to the MAUP have been proposed (Fotheringham, 2000; Fotheringham, Charlton & Brunsdon, 1998; Fotheringham & Wong, 1991; King, 1997), but have rarely been implemented in place and health research.

Place-based health research would benefit from both a greater knowledge of the patterns of movements of people, and insight into the heterogeneity of context associated with these movements within the population of interest. Capturing interactions with neighbours, such as borrowing tools or a cup of sugar, would occupy a smaller spatial scale than the walking environment; the local availability of healthy foods or accessibility to health services provision is meaningful only if people shop in their own neighbourhoods, or live close to a medical clinic. Approached differently, the intractable task at hand is to determine the most appropriate scale at which places influence a specific health behaviour or outcome; or, ideally, to allow for flexible scales suited to the space-time patterns of every individual. Although the link between people and their contexts may be strong at the local level, modern life involves more frequent movement at a variety of temporal and geographic scales. People may commute hundreds of kilometres a day, change jobs multiple times throughout a career, holiday thousands of kilometres away, and live for prolonged periods on several different continents.

The influence of place also changes over the lifecourse. Children are more likely to develop stronger attachments to locations much closer to their place of residence: longitudinal analyses show that the quality of places early in the lifecourse has a significant effect on health outcomes later in life (Curtis, Southall, Congdon & Dodgeon, 2004). As children develop into adolescence, social and physical bonds to places near their residence are diminished due to an increase in relationships outside home neighbourhoods, increased mobility, and independence (Schiavo, 1988). This trend of increasing mobility and spatial

extent carries into adulthood until the later stages of the lifecourse when there is a return to stronger attachments with specific places.

Expanding on these notions, it would seem prudent to consider the spatiality of health determinants at multiple scales, including those places that are geographically distant yet influential. For example, a combination of increasing mobility, culturally-influenced agricultural and animal management policies contributed to turning the spread of SARS into a pandemic. In the closing weeks of 2002, the first 'new' disease of the 21st century – SARS – emerged in southern China. Within days, this severe respiratory infection had leapt to Hong Kong, Vietnam, Singapore, Canada, Germany and beyond. Over the next eight months, 8,000 probable SARS cases and more than 750 deaths were reported in 26 countries (Pearson, Clarke, Abbott, Knight & Cyranoski, 2003). The individuals exposed to SARS where somehow interrelated in their travels, relied on existing spatial networks, and could be tracked through space and time. Greater knowledge of the changing geographies of place and health hinge on improvements in our understanding of the components related to the movement of people and materials, as well as how these components influence the contexts in which people live and materials are put to use. When we then incorporate the notion of lifecourse to recognize that the seeds of disease may possibly have been planted many years previously, it appears that the places where health outcomes or behaviours are measured are not necessarily the same places where exposures to context or diseases processes occur.

The premise thus far is that current thinking about places and the boundaries that define them should be revised given that human activities related to health outcomes are not necessarily synonymous with geographical

adjacency. In the following discussion, we turn to conceptualizations of place in support of extending conventional notions of place to a time-geographic perspective. Rather than a focus on using places as a surrogate for context in health research, it would seem logical that place-based health research should evolve to distinguish the notion of place as it is defined by the activities of individuals in space *and* time. Naturally, it is appealing to examine compelling evidence to show that these places, while dissimilar to conventional geographic boundaries, may be similar among individuals with similar attributes and social-economic characteristics (Kellerman, 1989; Kwan, 1998). The following section examines the possibilities for reconceptualizing place from the perspective of time geography, which provides the basis for analysis of individual activities in time and space, and can extend place-based perspectives to incorporate dynamic human and connective processes through which places evolve (Pred, 1983).

Context as space-time ecology

The logic of time geography is oriented towards the development of an approach to contextual research where physical, mental and socio-cultural aspects and their mutual interrelationships are part of the analysis of human agency (Hägerstrand, 1970; Hägerstrand, 1985). It begins from the evident reality that all human activities have spatial and temporal dimensions: activities occur at particular places for limited durations. The approach evolved from Hägerstrand's observations about the need to reveal the context of human action, where time and space are the principal foci for social analysis. Forms of

interaction – social and otherwise – are recognized as spatial processes (Ellegard, Hagerstrand & Lenntorp, 1977; Pred, 1977).

Time geography rests on the notion that the individual is the smallest indivisible unit in social contexts, and that the locations and movements of individuals can be followed and visualized as continuous paths in spatial and temporal dimensions. Unlike conventional place-based health research, which is usually limited to analyses based on residential location, a time geographical approach allows for the examination of place as the spatial, temporal and contextual terrains that influence individual health status; many of these terrains are not necessarily geographically proximal to one's residential neighbourhood. The challenge, at least from a population health perspective, is to comprehend the dialectic between the individual and the society, or the interplay between individual behaviour, the interactions between people, and the more structured relationships occurring between people and their institutions in context (Miller, 2001; Parkes & Thrift, 1980; Pred, 1981).

In time geography, time and space are joined in a space-time context where events and process unfold in sequences of situations. Processes are shaped by individuals' 'paths' and 'projects' in concrete space-time contexts. This quite simple conceptualization can be represented by a simple data structure to describe human movement and activities, and consists of a coordinate vector (x,y,t,a) which defines the spatial location (x,y) of an activity (a) at a specific time (t). The concept of 'project' pertains to the physical and virtual activities of individuals (a), such as visiting a physician. The space-time 'path' describes a person's movement from one location to another in two-dimensional space, with time (z) represented by the z-axis orthogonal to place. The path is

vertical when an individual is stationary at a specific location (x, y) and becomes more horizontal when moving through space. The slope of the path is determined by the movement velocity – a result of travel mode constraints. Paths can converge and diverge. Figure 2.1 illustrates the space-time paths of two individuals who at some point share time-space at a local café, but live and work in different locations.

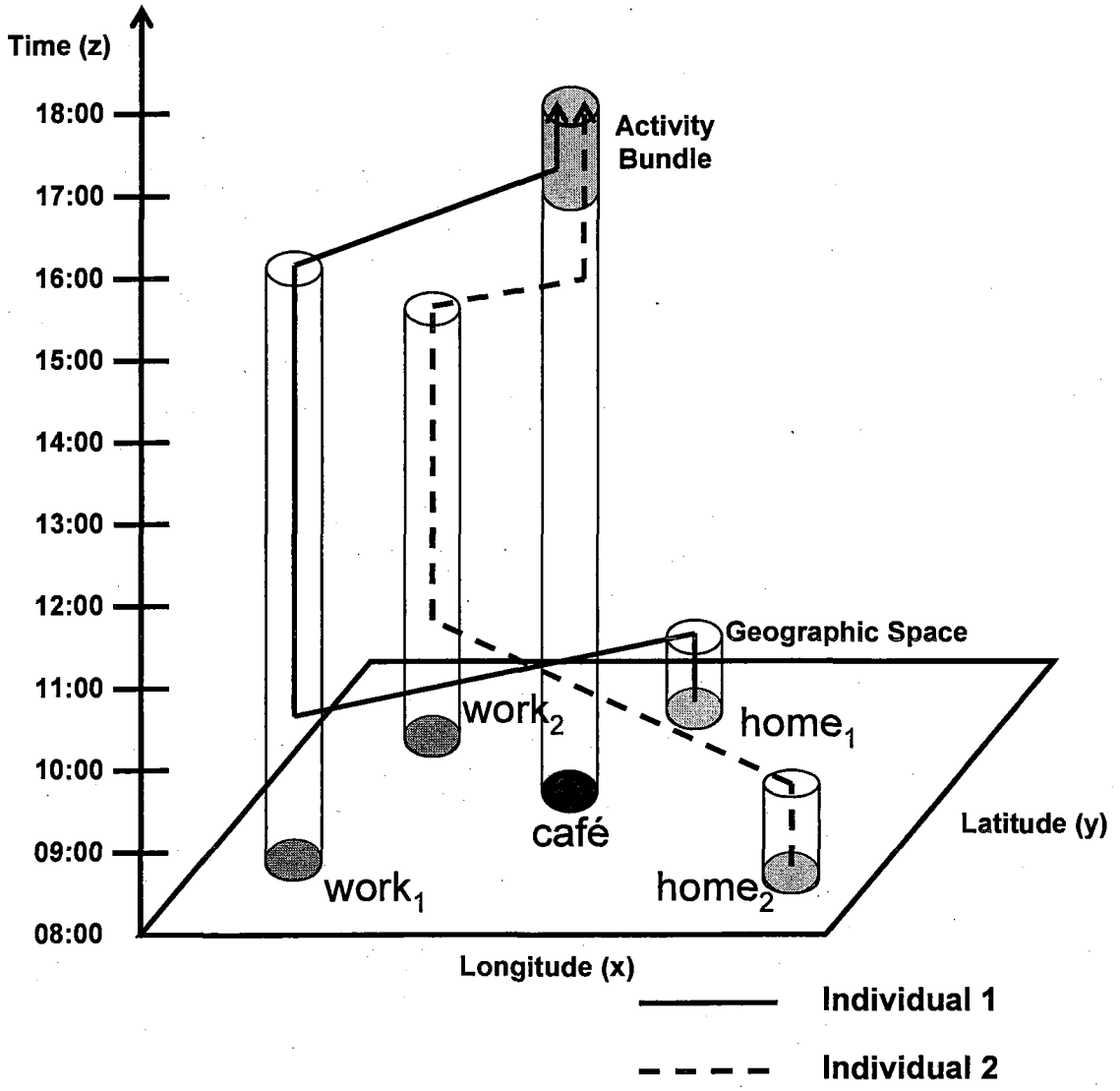


Figure 2.1 *Space-time paths of two individuals.* Time spent at café represents the 'convergence' of two paths and is also called an activity bundle. The sharing of moments in space-time provides insight into the spatiality of social interaction. Source: After Hägerstrand (1970).

Note, however, that convergence could also occur between people and environmental hazards, pathogens, or any such characteristics of places, and that paths may vary in duration from a few minutes to entire lifetimes (Kwan, 2002).

Variations in space-time pathways and activities are subject to a taxonomy of dimensions related to human agency (Hägerstrand, 1970; Pred, 1977). Three dimensions—capabilities, convergence and authority—are crucial components shaping the activities of individuals, and give emphasis to the significance of power relationships in the structuring of context. The capability of individuals to pursue any activity is influenced by physical and social conditions, genetic predisposition or the latitude to acquire and control resources for personal gain. These activities may coincide, or converge in space and time with other people, tools or resources, leading to variations in the levels of social interaction of support. However, human agency can be restricted territorially by forces asserting influence and control. Territoriality is an attempt by an individual or group to affect influence, or control people, processes, and relationships, by delimiting and asserting control over a geographic area (Sack, 1986). For example, municipal governments can modify zoning rules to allow more or less healthy forms of development; they may also dictate public transportation timetables making it more or less difficult for some individuals to travel efficiently. The nexus of these dimensions leads to the structuring of context and invariably the processes leading to the social structuring of society (Parkes & Thrift, 1980; Pred, 1983). An agency-based perspective places a greater emphasis on the significance of power relationships as a determinant of spatial bounding. Thus, places are constructed to some degree by the dynamic

social relations and power struggles among groups in society (Delaney & Leitner, 1997; Massey, 1993; Pred, 1983). These groups are not necessarily located proximally to the places they influence, but they can encompass more or less formal arrangements between people, places, and the structures (governance structures or institutions, for example) of society.

Individual activities can be categorized into two types. Fixed activities are not easily rescheduled or relocated. These include things like work schedules or meetings, or home activities such as sleeping. From a spatial perspective fixed activities are like space-time anchors since additional, and usually flexible, activities must occur at the spatial and temporal gaps between fixed activities (Hägerstrand, 1970). These additional activities, such as shopping or recreation, are called flexible activities because they can more easily be rescheduled and may occur in different locations. The capacity of an individual to perform different types of activities can be influenced by certain dimensions of agency, likely as a result of their simultaneous presence in time-space. An individual with a physical disability may be subject to capability and authority dimensions thus limiting her ability to carry out flexible activities. For example, certain locations may be inaccessible to people with disabilities.

Social Connectivity and Human Activity Spaces

While time geography cannot provide a solution to issues of space bounding, particularly those having to do with the division of space or with appropriate scale, it can provide a useful framework for thinking 1) about how individuals are interconnected across space (typically beyond statistical or administrative boundaries), and 2) about the characteristics of space required

to capture their projects and paths, or the spatial morphology of an individual's activities. Since the focus is on the space-time activities of individuals, and with how individuals who belong to a variety of social or physical groupings interact and overcome constraints to achieve a particular objective, it is logical to consider that places could be usefully observed as elements in social networks and not just as a physically-bounded space.

Social network analysis has been making substantial contributions to research on health issues (Berkman, 1982; Berkman, 2000; Brenner, Norvell & Limacher, 1989; Hawe, Webster & Shiell, 2004; Watts, 2004), and is well established in the field of social epidemiology. Central to the investigation of networks is the analysis of structure, or relational data derived from the patterning of social entities such as people, groups, or organizations (Wasserman & Faust, 1994; Wellman & Berkowitz, 1997). Several variables may influence the scope and intensity of social networks. For example, residential stability will influence the formation of locality-based friendships and participation in local activities, thereby increasing local attachment and social cohesion (Sampson, 1991). On this view, social structures arise from networks and are partly responsible for determining individual behaviour by shaping the flow of resources that determine access to opportunities of constraints on behaviour. These structures, however, may not necessarily conform to the conventional spatial containers of context (census tract, postal code areas, and traditional neighbourhoods). The lived existence of people is constituted through the contextualization of social structures and relations in everyday life. Limiting these experiences and connections to a specific context will jeopardize the opportunity to consider more fully the spatial and dynamic processes

characteristic to one' s health status, and life in general. In essence, limiting the influence of context runs the risk of divorcing geographic context from social context (Gatrell, 1997).

The manner in which social structure is associated with the geographical distribution of health status is also a by-product of what people do at particular locations. According to Giddens (1984) individuals structure time and space socially thus producing unique spatial configurations of context. This relational perspective of context acknowledges the ingredients of mobility and social networks in a recipe of daily routine. The product of these routinized activities can be represented as activity spaces which are geometric indicators of the subset of all locations an individual has had contact with as a result of her activities (Golledge & Stimson, 1997). These spaces have the potential to replace traditional methods of space bounding as they more accurately represent the context within, and the degree to which places affect human wellbeing. An activity space is essentially a two-dimensional form or spatial boundary that is created by the spatial distribution of locations where an individual performs an activity (Newsome, Walcott & Smith, 1998; Schönfelder & Axhausen, 2004). Activities such as commuting to work, purchasing food, or socializing with friends and relatives are important elements of an individual's activity space. Activity space concepts have been employed in health research to assess the frequency of health care facility use by the elderly (Gesler & Meade, 1988), in the optimal location of health care facilities (Cromley & Shannon, 1986), and in the development of hybrid exposure assessment models (Jerrett, Arain, Kanaroglou, Beckerman, Potoglou, Sahsuvaroglu et al., 2004).

Collectively, then, these theoretical developments regarding individual agency, social structure, and activity space provide a starting point for exploring the influence of context on health. Coupled with population health research that is beginning to show the "ecosocial" nature of the varied and simultaneous influences of context upon health (Krieger, 2001), it can be seen how human agency is embedded in social structure that both guides and is guided by the pursuits of everyday life.

The Logic of the Healthscape

Modeling an individual's time-geography results in a space-time pattern representing the full spatial extent of her activities over a specified period of time. Rather than employing administrative boundaries, or areas defined by social, economic, or other conditions of the population in a given area, time-geographical information represents the landscape of context(s) relevant to exploring variations in health status. The concept of landscape is not foreign to health geography research. Previous works have examined landscapes of despair (Dear & Wolch, 1987), landscapes of health-care restructuring (Kearns & Barnett, 1997; Kearns & Gesler, 1998), and therapeutic landscapes (Gesler, 1992; van Ingen, 2004; Williams, 1999), and have helped to legitimize the concept of landscape in the development of place-based health research. Extending the concept of health landscape we suggest the term healthscapes for use in place-based health research. A healthscape is a spatial notion that helps to identify the contexts associated with geography unique to every individual as expressed through the temporal and spatial activities of daily life. From the perspective of spatial bounding, healthscapes are the canvas on which to

investigate the spatial configuration of the relationships between individual agency and the structural attributes of context relevant to health.

Table 2.1 summarizes the key components of a healthscape approach. It provides a common information structure for studying associations between place and health – these components include many key characteristics of conventional place and health perspectives. A healthscape approach for place and health builds on conventional perspectives with the addition of what Cummins and colleagues (2007) call a relational perspective; specifically, those attributes of people or places as they are defined by the properties of time and spatial relationships. The collection of time-geographical information provides the information necessary to explore how people and contexts are related in time and space as defined by the space-time pathway. The healthscape thus defines the relationship among attributes of places and the individual activities that occur within and beyond them.

From an ontological perspective, the terms 'map', 'boundary', 'inside' and 'outside' represent spatial specifications of the concept of 'place' (Smith, 1996). Expanding these notions to the healthscape, individuals' 'activities', or the projects an individual undertakes along her space-time path, are defined by the constraints imposed by the place as well as the determinants of an individual's health. However, little is known about how the characteristics of an individual's space-time path, or healthscape, affects health.

Table 2.1
Properties of the Healthscape Approach for Place and Health Research

1. Properties of Place
   - Geography (altitude, slope, boundaries, connectedness)
   - Influence on human agency (capability, convergence, authority)
   - Land Use (land, urban, parks, industrial)
   - Function (consumption, housing, agriculture, recreation)
   - Objects (barriers, monuments, buildings, water bodies)
   - Meaning (personal, social, safety, pleasure, utility)

2. Properties of Context
   - Scale of Influence (local, regional, national, global)
   - Culture(s) (sports, holidays, festivals, food)
   - Ecological (weather, pollution, air, water, soil)
   - Customs & Regulations (laws, policies, regulations, governance)
   - Social Capital (reciprocity, trust, connections, propinquity)
   - Health (walkability, safety, accessibility, conviviality)

3. Properties of Spatial Relationships
   - Adjacency (direction, distance, conflicts)
   - Connectivity (networks, communications)
   - Containment (area, transivity, perimeter)
   - Compactness (circularity, thickness)

4. Properties of Time
   - Frequency (diurnal, weekly, yearly)
   - Relative (births, deaths, birthdays, retirement, generational)
   - Meaning (working, pleasure, holiday, night, weekend)
   - Perception (efficiency, presence, intensity)

5. Properties of People
   - Activities (working, socializing, exercising, consuming)
   - Attributes (age, gender, health status, genetics, occupation, education)
   - Mobility (constraints, infrastructure, means, purpose)
   - Associations (familial, community, religious, voluntary)
   - Lifecourse (infant, child, teenager, adult, elderly)

Sources: (Berkman, 2000; Cummins, Curtis, Diez-Roux & Macintyre, 2007; Curtis et al., 2004; Diez Roux, 2002; Frank & Engelke, 2001; Frolich et al., 2001; Golledge & Stimson, 1997; Jones & Moon, 1993; Krieger, 2003; Macintyre & Ellaway, 2003; McLafferty, 2005; Walcott & Smith, 1998).

A healthscape can be more formally represented as: 1) objects (the properties of places, contexts, and the space-time paths of people), and other features of context assumed to exist in the healthscape; and, 2) the relationships that hold among them, or from a geographical perspective the topological nature of objects and context. Places display two types of completely bounded objects: those of a bona fide character and those fiat objects created by human actions (Smith, 1995; Smith & Mark, 1999). Bona fide boundaries include physical attributes of places such as topography, waterways, or other features, and express differences in the underlying mulit-dimensional reality of the healthscape. Fiat boundaries arise from acts of human decision, administration, or fiat, laws or political regulation. These boundaries include political and administrative units, borders, property boundaries or other spatial objects of human invention. Bona fide and fiat boundaries are common in conventional place and health research. The healthscape represents a third type of boundary, as defined by the individual and her own characteristics of time geography. Healthscapes thus cross bona fide and fiat boundaries, resulting in a set of 'fuzzy' spatial objects that are more amenable for examining the relationships between place and health at different scales without spatial constraints.

The usefulness of the healthscape approach is that it includes the basic elements of time geography (x,y,t,a) data. However, selection of the boundary that correctly captures context, especially those that are health relevant, can be contested; the challenges of spatial bounding become more apparent when quantitative approaches to place and health questions require clear boundaries over a variety of temporal scales. To cope with these challenges, we might

consider the following actions. First, researchers should consider the pattern of an individual's space-time path as a guide to how events and activities that are related to health are to be defined spatially. The act of assigning boundaries on space unique to the persons under study may confer additional characteristics of place relevant to human health, but may also lead to practical difficulties in analysis as multiple individual boundaries are constructed. Second, due consideration should be granted to the meaning of places as they relate to health status. Third, researchers should be aware of how the geographies of the lifecourse impact how an individual's space-time activities are bounded over time, as well as how places evolve independently over time to influence individual action and agency. Collectively, these considerations are important to the practice of empirical research and to the development of context-based health policy interventions.

Positioning People and Context in Space and Time

The potential to expand conventional place-based health research to include space-time activity information requires a re-examination of existing data collection procedures as well as the development of new tactics for the collection and analysis of space-time activity data. Gathering information on the location and timing of human activities is notoriously difficult: space-time activity data are usually expensive to obtain and prone to error (Golledge & Stimson, 1997). In addition, researchers must keep in mind issues associated with data confidentiality as well as the potential to introduce bias from non-compliance of participants in providing personal information. Here, we examine current and evolving practices in the collection of space-time activity data, and

associated issues of privacy and confidentiality. We also provide a rudimentary introduction to the analysis of these data for place and health research.

Data on the temporal sequencing of human activities are usually derived from time-use studies. These usually consist of diary-based instruments designed to understand time-use and activity patterns at a diurnal scale (Harvey & Pentland, 1999). Diary-based data infrequently provide accurate information of location (Janelle, Klinkenberg & Goodchild, 1998). Bias can easily be introduced as a result of the reluctance of participants to document their movements and activities at regular intervals over extended time periods. There is also the possibility of introducing additional bias resulting from participants having to recall numerous activities occurring over longer time periods. Large scale time-activity studies can provide fairly detailed accounts of daily activities as well as supplementary sociodemographic information and data on household and mobility characteristics. For example, an activity study in Canada collected data that were used for international activity pattern comparisons and in the development of air pollution exposure assessment models (Leech, Nelson, Burnett, Aaron & Raizenne, 2002; Leech, Wilby, McMullen & Laporte, 1997). Studies that are national in scope are infrequent and lack activity information coded by location. An exception to this includes longitudinal health studies where respondents are followed over time and the details of their major activity locations (space-time anchors), such as home and work locations, are recorded. For example, yearly census data in Sweden providing information on residential location have been linked to a unique number provided to each citizen at birth. The unique number is also linked to medical and employment records, and can be used to track an individual's

interaction with government services over the lifecourse. There are also rare time-activity studies with data coded for actual spatial location (Elliott, Harvey & Procos, 1976).

Time-activity studies usually employ one of three methods to determine time-use. Recall methods require subjects to recall and report activities during a specified time frame and rely on the ability of the subject to remember the location and type of activity at a later time. Another approach, called shadowing, requires agreement by subjects to be followed by a researcher over a specific time period. Subjects are more likely to modify usual activities and routines in an attempt to make observations seem more interesting and the researcher may choose to conduct longer assessments or intermittent assessment to overcome this intentional bias. A third approach utilizes time diaries in which subjects record their activities, either in free format or at predetermined time intervals. Previous experience suggests that diary methods produce the best data, although there are unresolved issues associated with the willingness to report specific activities (usually deemed to be unimportant by the subject), as well as underreporting of shorter trips or stops during a multipurpose trip (Pas & Harvey, 1997).

To overcome some of the difficulties inherent in the collection of georeferenced time-activity information, researchers can modify survey methods or adopt new technologies to facilitate the collection of space-time activity data. Redesigned survey methods could include the use of web-based survey techniques which allow the respondent to link individual activities to locations on maps. Users can also add information about travel modes and other contextual information relevant to the study, such as responses to questions

about health status. Another option is to access auxiliary databases containing space-time activity information that were not initially designed for the purposes of conducting place and health research. For example, it is possible to obtain cellular phone records from service providers for the purposes of research provided that individual-level information about the subscriber is not published. Several studies have used data from mobile networks to map and explore the structure of social and communication networks, as well as to determine respondent locations with a relatively high degree (15-30 m) of accuracy in urban locations (LaMarca, Chawathe, Consolvo, Hightower, Smith, Scott et al., 2005; Onnela, Saramäki, Hyvönen, Szabo, Lazer, Kaski et al., 2007). It is also possible to approximate human movement through time and space from electronic data streams, which can reveal much about activity patterns. Credit or debit cards and fund transfer records can provide details about location and time of consumption, the nature of these locations, as well as descriptions about the services or products purchased. The ability to access these data is constrained by privacy legislation and, if the data are available, they usually have signficant commercial value and are likely to be expensive, or even unavailable for research purposes. Researchers may also look to existing data collection structures on the Internet and develop agreements with website authors to examine the data for research purposes. For example, researchers recently analyzed a database from an online website that tracks one dollar bills to model the spatial movement of individuals and the geographic spread of infectious disease (Brockmann, Hufnagel & Geisel, 2006).

But all of these methods give only partial data on a person's movements, and raise major issues of privacy. Location-aware technologies (LAT) consist of

devices that can report or log their geographic location in near-real time. These technologies have the potential to greatly reduce the cost and improve the accuracy of collecting space-time activity information (Murakami & Wagner, 1999; Stopher, FitzGerald & Zhang, 2006). There are several georeferencing methods employed by LATs including radiolocation, radiofrequency identification, and geosensor technologies. Perhaps the most widely used and most accurate approach is the use of global positioning systems (GPS). To date GPS tracking has been concentrated largely in the study of travel patterns, particularly in conjunction with household travel surveys (Wolf, Schönfelder, Samaga & Axhausen, 2004), and studies of species range in wildlife and biological research (Hulbert & French, 2001; Phillips, Elvey & Abercrombie, 1998; Rodgers, 2001).

More recently innovations in GPS tracking and logging technologies have resulted in the development of wearable or portable devices (Rainham, Krewski, McDowell, Sawada & Liekens, 2008). Wearable GPS uses differences in timing data from a constellation of satellites to determine an individual's location. This information can be logged passively or sent in real-time using cell phone networks to a remote server for further analysis, which allows researchers to map an individual's space-time path through multiple contexts. These contexts may include path anchors such as home or workplace, or may include resources in areas adjacent to these areas that differ in terms of their ability to promote or impair health.

Although in its infancy, the use of GPS technology for human tracking presents an enormous opportunity for improving our understanding of how context as represented by the space-time activities of individuals can influence

health and well being. Recent applications of GPS technology for health research have been concentrated on physical activity assessments and human exposure studies. For example, lightweight GPS receivers were used to assess physical activity as measured by the velocity of walking and running (Schutz & Chambaz, 1997), to determine the mechanical power of walking (Terrier, Ladetto, Merminod & Schutz, 2001; Terrier & Schutz, 2005), and to geographically contextualize accelerometry data or the locations where physical activity occurs (Rodriguez, Brown & Troped, 2005). Several studies have also used wearable GPS loggers to validate time-activity diary data (Elgethun, Yost, Fitzpatrick, Nyerges & Fenske, 2007; Phillips, Hall, Esmen, Lynch & Johnson, 2001), and to track individual exposure to chemicals in community-based exposure assessment research (Elgethun, Fenske, Yost & Palcisko, 2003). The utility of wearable GPS receivers is enhanced when linked to additional sensors that can monitor physiology, or specific exposures such as air pollution (Milton & Steed, 2007; Pandian, Mohanavelu, Safeer, Kotresh, Shakunthala, Gopal et al., 2007).

There are clearly important ethical and privacy issues associated with the tracking and recording of a person's activities in space and time, and people willing to wear such devices may not be representative of the general population. Wearable GPS and other LATs can provide accurate point level time and location data, thus enabling, through visualization and mapping techniques, an estimate of an individual's residential, work, or other locations that form aspects of daily or weekly routines. The presentation of individual space-time information can lead to 'map hacking' or inverse address-matching where geographic information systems and associated technologies are used to 'hack'

published maps and recover large proportions of original addresses and co-location data on individual respondents (Armstrong & Ruggles, 2005). Exploited to the extreme, LATs could be used to invade personal privacy by preventing an individual from specific locations in space and time, or from pursuing a desired space-time trajectory. The possibility of this form of control have been labelled as 'geoslavery', in which an entity (master) surreptitiously monitors and exerts control over the physical location (as well as time, location, speed, direction) of another individual (Dobson & Fisher, 2003). Several obfuscation techniques are now available to protect data confidentiality, including geographic masking, software agent-based data confidentiality, and techniques for mobile objects (Armstrong, Rushton & Zimmerman, 1999; Boulos, Cai, Padget & Rushton, 2006; Duckham & Kulik, 2005). In reality, concerns about the negative use of locational data must be balanced against the potential for societal benefit accruing from an improved understanding of how place influences an individual's space-time path, the activities they undertake, and ultimately their well being. Carefully done, such research can be based on informed consent of the study volunteers.

Analysis of Space-Time Data

The collection of space-time activity data leads to the creation of very large datasets and presents difficulties for analysis. For example, GPS tracking of an individual can produce approximately half a million track points in a week; each track point is recorded as a single observation with latitude, longitude, time, date, velocity, and measures of accuracy (Figure 3).

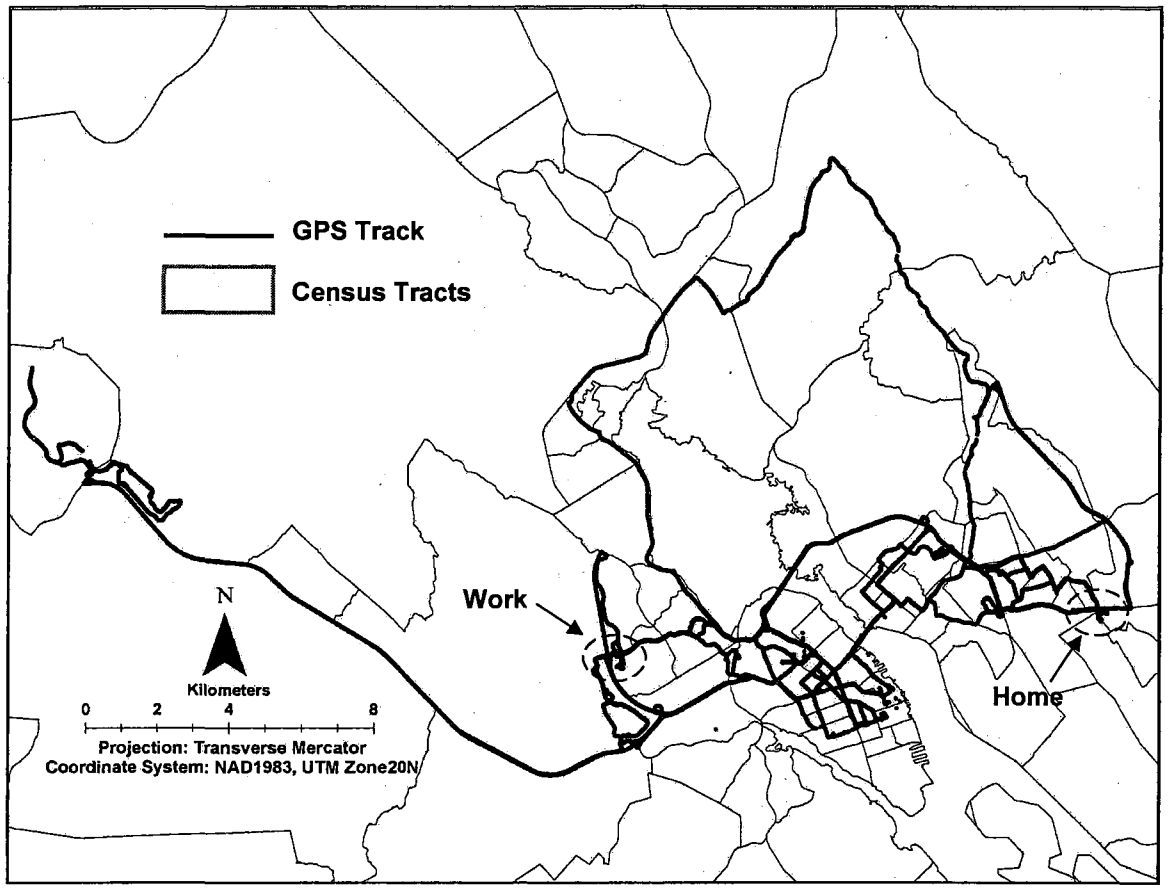


Figure 2.2 *Space-time path of an individual for seven day period.* Path is overlayed onto census tract boundaries for comparison.

While it is relatively straightforward to import and visualize GPS data in most standard geographic information system software, it is extremely difficult to conduct meaningful data analysis using standard geographic and statistical routines. Standard routines are usually unable to efficiently display and run location and attribute queries of spatio-temporal data unless there is substantial reduction of data space. This issue is compounded when space-time data are linked to activities and other individual attributes such as health determinants derived from questionnaires. The emergence of new quantitative and computational techniques for exploring space-time activity information will

benefit place and health research because of the ability to measure individual 'exposures' to multiple contexts.

Although no integrated methods yet exist, several approaches have been developed to explore and analyze space-time activity data. These approaches can be categorized into three areas: visualization and related analytics, multidimensional time-activity sequencing methods, and pattern morphology metrics. Interactive and dynamic visual representations are very useful for understanding spatial and spatio-temporal data, as well as underlying phenomena. Kwan and others (Kwan, 2000; Kwan & Lee, 2004; Kwan & Weber, 2003) have used GIS to construct three-dimensional space-time aquaria to visualize human activity density patterns. In the space-time aquarium, the vertical axis represents the time of day (or the passing of time at a location) and the horizontal plane (x, y) represents the spatial extent of the study area or space-time pathways. With this type of geovisualization it is possible to identify the contexts relevant to an individual (or group), and to investigate how the space-time pathways of individuals from different groups (gender, social, cultural) may then be contrasted. The spatial relationships one to another, such as co-location in time and space, could then be linked to health and/or contextual data. In related work, Andrienko & Andrienko's (2007) analysis of dynamic collective behaviour have extended more common exploratory methods of spatial and temporal data to describe both individual movement behaviours as well as momentary (temporal) collective movement behaviours. The purpose of these visualization approaches is to identify the possible patterns in human movement data (space-time pathways) using mathematical functions and relate

them to properties of space and time, properties and activities of individuals, and relevant external phenomena.

New computational techniques for exploring space-time activity data adapt multidimensional sequencing alignment methods from genomic research to assess similarities (and differences) among activity pattern and location data. Activity data are coded according to a predetermined or adaptive guide and ordered by time. For example, activity data for sleeping might be coded as 'zz', work might be coded as 'wk', and distance codes can be associated with each activity so as to assess their spatial extent. Activity sequence alignments are used to find the primary behavioural groupings and to identify socio-economic and other characteristics of the group.

To date, few activity sequence alignment techniques have been applied to the analysis of health outcomes. Wilson and Harvey (Wilson & Harvey, 1999) analyzed almost 250 time-activity patterns of Canadian women and were able to identify 15 different activity classifications (such as paid work, recreation, socializing, or family care), as well as a basic understanding of location and whether other individuals were present as activities were performed. These data would be extremely useful for further study to understand whether the propensity to perform certain activities for specific time periods is related to measures of health and well-being. More recent analyses have used multidimensional activity sequence methods to simulate the way individuals solve activity scheduling issues based on decision rules induced from empirical activity data (Joh, Arentze & Timmermans, 2001). These data are particularly useful for exploring the influence of various constraints on individual choice,

and whether these constraints as well as the ability to modify activity schedules, are associated with the characteristics of places.

Finally, developments in wearable positioning and geographic information technologies provide an opportunity to quantitatively measure an individual's exposure to multiple contexts, and to compare these measures against exposures derived from conventional boundaries such as census tracts. The most useful locational attributes are points with precise location (latitude and longitude) coordinates measured from GPS or from geocoding. Building on John Snow's dot mapping investigation of mortality from cholera in 1854, the analysis of point patterns comprises a significant portion of the methodological tools used in ecology, geography, and spatial epidemiology (Gaston, 2003; Gatrell, Bailey, Diggle & Rowlingson, 1996; Goodchild & Janelle, 2004). Using point pattern analysis, it is possible to delineate the spatial extent of an individual's range (boundary), as well as the intensity of activity among locations within a person's boundary. Additional metrics such as fractal analysis and Markov chain models may also be employed to evaluate movement patterns and to account for decision-making processes about how people negotiate their way through multiple contexts (Hung, Venkatesh & West, 2001). These characteristics of an individual's space-time path can be extended over time to detect changes in geographic range and intensity through the lifecourse. In addition, the assessment of space-time paths can be performed for much larger population samples, thus allowing for measurement of group-level activity patterns in space-time. For example, geographic incidence of social activities among individuals with low income may demonstrate a tendency towards clustering in a specific context. Kwan & Lee (2004) have demonstrated

that the space-time density of non-employment activity patterns of men are more spatially distributed than for women.

Extending conventional place and health research to incorporate data derived from GPS and other location-aware technologies will require the adoption of existing methods from time geography, and an expanded effort to develop new indicators of the qualitative and quantitative character of individual space-time paths. It is beyond the scope of this paper to comprehensively review methods for the analysis of space-time path data; rather, we focus on a small set of point pattern analyses relevant to our previous discussions about spatial bounding, as well as the utility of network analysis and activity spaces for place-based health studies. Point pattern analysis encompasses a set of techniques to identify and measure spatial processes from point data (Arcury, Gesler, Preisser, Sherman, Spencer & Perin, 2005; Galton & Duckham, 2006). Points generated from GPS are inputs to point pattern analysis. These data can also be categorized according to time, activity, or, in the case of an epidemiological study, an exposure or health-event of interest.

A number of different point pattern analyses have been developed and four approaches are described here. Figure 4 provides an example of each method derived from GPS data recorded over a seven day period. The basic features of each point pattern approach are then described.

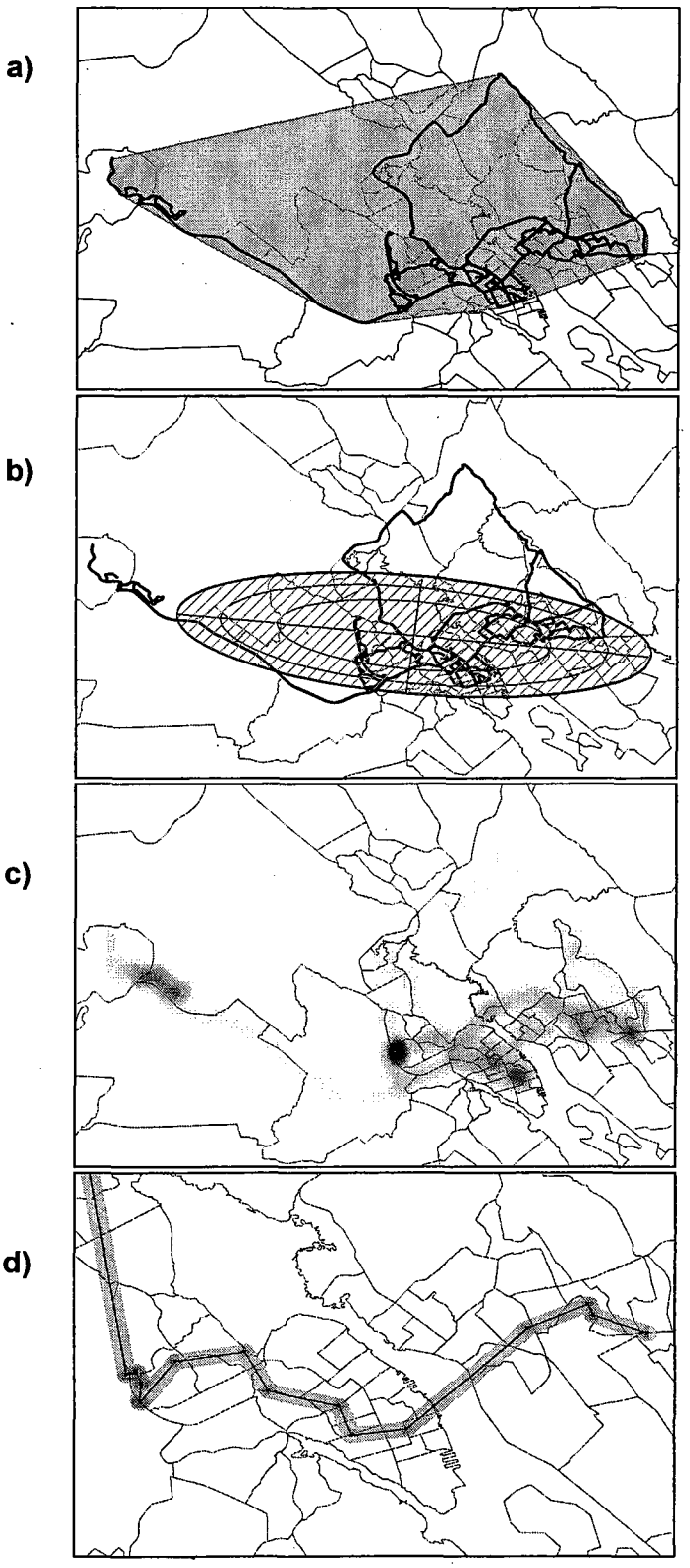


Figure 2.3 *Analysis of point patterns from an individual's seven-day GPS log.* a) Minimum convex polygon; b) Standard deviation ellipse; c) Kernel density estimation; d) Minimum spanning tree. All data overlayed onto census tract boundaries for comparison.

a) Minimum Convex Polygon (MCP): The MCP is created by connecting the outermost set of data points representing an individual's locations to form a polygon with no concave sides. MCPs are relatively simple to construct and are unaffected by spatial or temporal trends in the data. Polygons can be constructed for each individual providing an approximate boundary, or spatial extent, of their activity patterns. There are several drawbacks to using a MCP approach. MCPs are nonparametric, and thus uninformative in terms of specifying whether specific contexts are used more or less frequently. The polygons are also sensitive to sample size, with the size of the polygon increasing with the number of sample locations measured. For example, if an individual makes a weekly trip to a location quite distant from their home to a meeting in another city by air, then the calculation of the MCP would be influenced by the outlier activity resulting in an overestimation of spatial range. Furthermore, MCP approaches ignore bona fide boundaries such as lakes, harbours, or other barriers that constrain human movement. These limitations have led to the development of more refined, statistical approaches

b) Standard Deviational Ellipse (SDE): SDEs capture the spatial distribution of an individual's space-time pattern around a mean center and an ellipse at one or more standard deviations from the center. Variation in the x- and y-coordinate values may be used to generate an ellipse with major and minor axes reflecting the directional variation of the point pattern (de Smith, Goodchild & Longley, 2007). The orientation of the ellipse is determined by the sign of the correlation between location coordinates. SDEs are often used to represent human (and routine) activity spaces (Arcury et al., 2005; Schönfelder & Axhausen, 2004). SDEs provide information on the concentration or dispersion

of an individual's location in several contexts, and illustrate the predominant directions of those locations. Different activities or exposures can be modeled using weighted SDEs, and it is possible to specify a different location for the mean center, such as home, work, or other activity locations. For example, the shape of an SDE would be much narrower for an individual who regularly commutes longer distances to work than for an individual who lives closer to work or other amenities. SDEs are less sensitive to sample size and outlier data; however, they also ignore boundaries that constrain mobility.

c) Kernel Density Estimation (KDE): KDE is an interpolation or smoothing technique that generalizes events or points to the area in which they are found, and leads to a calculation of a value for any point, cell or sub-region of the study area (Downs & Horner, 2007). KDE is widely used in many applications including crime hot spot analysis (Chainey, Tompson & Uhlig, 2008), wildlife home range estimation (Gross & Yellen, 1999) and health research (Bithell, 2006). Kernel density estimates have also been calculated for large cross-sectional data sets of individual space-time paths derived from transportation surveys (Kwan, 2000). KDE is of particular relevance to place-based health research since it identifies both an individual's spatial boundary as well as the intensity to which specific areas within the boundary have been used. While home and work locations would figure prominently, the advantage of KDE is the ability to identify additional contexts of particular importance or meaning, or contexts typically outside of the home census tract. For example, an individual may live in an area east of a river, work in an area west of a river and routinely visit a pub in another area, and travel by automobile between each location. However, a challenge of using KDE is how to account for processes that operate

in linear or networked space. KDE algorithms are now being adapted to account for movement data using network rather than Euclidean distances (Downs & Horner, 2007).

d) Minimum Spanning Trees (MST): The design of urban areas and road networks invariably constrain an individual's mobility as well as the ability to perform activities supportive to health (Chainey et al., 2008). Using graph theory it is possible to calculate the size and shape of an individual's space-time path from the paths taken over a specific time period. A graph essentially consists of a set of nodes or vertices and edges, such that each edge connects a pair of nodes (Gross & Yellen, 1999). A path in a graph is a unique sequence of nodes with a distance measured by the total length, or a weighted value of each connecting edge. A tree that includes all of the vertices in the graph is a spanning tree; the minimum spanning tree is the tree in the path with the shortest total length or weight. When applied to place-based health research, each node represents an activity location and edges represent the network path taken by an individual to reach each location. Previous work has helped to determine the structure and size of the MST to quantitatively approximate an individual's perception, knowledge, and use of space (Schönfelder & Axhausen, 2004). MSTs can also be transformed into areal units by buffering around the vertices of the tree.

Several disciplines in ecology and geography have developed approaches to the analysis of individual space-time path and activity, including: metrics of paths between places, mechanistic home range analyses, graph and network theories, and measures (area, edge, elevation, landscape class, distance) from landscape ecology (Giles & Trani, 1999; Moorcroft & Lewis, 2006; Turchin, 1998;

Urban & Keitt, 2001). Probably the most useful approach to modeling GPS data is kernel density estimation because it provides both a spatial boundary as well as information about the intensity of activities in different contexts. Researchers should be open to the idea that the contexts relevant to health may not be conveniently found in one area. Rather, individuals may spend time in contexts that are not spatially adjacent to home or work places, and each of these contexts may have relevance to different health outcomes or behaviours. Spatial boundaries derived from accurate space-time path information enables researchers to examine the potential for misclassification when using readily available administrative areal units. In addition, point pattern measures of individual space-time path data encourage greater focus on characterizing places as well as on the position of places relative to each other. An issue with the methods described so far is the assumption that places or other health-related influences operate on population health independently of conditions in other areas. To this extent, researchers may choose explore the sensitivity of results derived from point pattern, and other analyses of space-time path data, to changes in boundary characteristics, size, and processes operating at broader scales.

Conclusion: A Path Forward for Place and Health Research

Conventional research interests and analyses in place and health research are limited by theories and approaches that ascribe a narrowly-defined representation of context to variations in health and their determinants. This paper provides an alternative perspective, based on the concept of time geography, which might offer a more dynamic and mindful understanding of

how place affects population health. The development of technologies and methods represents a promising step forward for empirical place and health research. The advantage of time geographical approaches is that, while reasonably precise individual-level space-time activity data are required, current limited descriptors of place can be expanded to provide a more rich and meaningful insight of how place affects population health.

Currently, the potential application of time geography to place and health research is far from being realized. There are very good reasons why time geographical approaches should be integrated into place-based health research, in a manner similar to the inclusion of a lifecourse perspective into mainstream epidemiology. First, conventional place and health studies need to move beyond conventional notions of place which are characterized by notions of health and context that are static in time and space. One of the most appealing features of time geography is that it is a heuristic approach for chronicling an individual's movement through multiple places and contexts over different time periods. Ultimately, these healthscapes will provide improved measures of exposure which can be used to understand which contexts are most relevant to health, in terms of location and duration, as well as how an individual's personal characteristics mediate place and health relationships. The current methodological approach in many place-based health studies relies on existing administrative boundaries, or modifications thereof, to derive the features of place to be associated with health outcomes. Data derived from mobile technologies indicate that individuals are not limited to a single context, and that their activities vary in time and space (Kwan, 2002; Miller, 2007; Phillips et al., 2001; Rodriguez et al., 2005). With very little information, it is possible to

construct a space-time path of loosely-defined activity locations and then explore the structure of the pattern by considering the connections individuals create among these locations and with other individuals. As more information is collected it can be used to assess whether space-time patterns vary according to health or demographic characteristics of the population under study.

Second, methods and technologies for time geographical research are currently available, and should be exploited more fully in empirical research efforts. Although it may not be plausible to record the space-time pathways of a large sample required for national or international level research, many place and health studies focus on individual cities and neighbourhoods where time-geographical approaches could be applied. By focusing on specific exposures or health outcomes, researchers can explore the scale at which processes related to context operate, and use this information to improve intervention planning. Time geographic methods are most powerful when linked to additional information about exposures and physiological measures. For example, the use of global positioning systems with personal air monitoring technologies has not only improved estimation of individual exposure to harmful substances, but has provided insights into how different contexts are associated with changes to health risk (Elgethun et al., 2003; Milton & Steed, 2007; Schutz & Chambaz, 1997).

Adopting a time geographical approach does not mean displacement of conventional or alternative approaches to the study of place and health. Certainly conventional empirical approaches have been valuable in emphasizing the role of place as a determinant of population health. We suggest time geography as a theoretically and empirically powerful adjunct to conventional

approaches. The relative simplicity and flexibility of time geographical and related theoretical approaches to place and health can improve our comprehension of the spatial and temporal interdependencies that exist between people and places. Future place and health research must thus develop conceptual approaches and analytical tools that explore the geometric, dynamic, and semantic properties of places and the people who inhabit them.

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Chapter 3

Development of a Wearable Global Positioning System for Place and Health Research

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Note: Formatted for the International Journal of Health Geographics.

What is already known on this topic?

- Global positioning systems can accurately determine the position of objects or people on the surface of the earth.
- Advances in the miniaturization of GPS technologies offers promise for human tracking studies.
- GPS signals are subject to a variety of interference potentially limiting the usefulness of GPS in some research areas.

What this study adds:

- A novel wearable GPS data logging device was developed to track people.
- The GPS device is sufficiently accurate to locate and correctly classify a variety of human activities.
- The ability to track people over extended periods of time facilitates the development of spatio-temporal data to accurately and objectively identify contexts relevant to health.

Abstract

Background: An increasing number of studies suggest that characteristics of context, or the attributes of the places within which we live, work and socialize, are associated with variations in health-related behaviours and outcomes. The challenge for health research is to ensure that these places are accurately represented spatially, and to identify those aspects of context that are related to variations in health and amenable to modification. This study focuses on the design of a wearable global positioning system (GPS) data logger for the purpose of objectively measuring the temporal and spatial features of human activities. Person-specific GPS data provides a useful source of information to operationalize the concept of place.

Results: We designed and tested a lightweight, wearable GPS receiver, capable of logging location information for up to 70 hours continuously before recharging. The device is accurate to within 7 m in typical urban environments and performs well across a range of static and dynamic conditions.

Discussion: Rather than rely on static areal units as proxies for places, wearable GPS devices can be used to derive a more complete picture of the different places that influence an individual's wellbeing. The measures are objective and are less subject to biases associated with recall of location or misclassification of contextual attributes. This is important for two reasons. First, it brings a dynamic perspective to place and health research. The influence of place on health is dynamic in that certain places are more or less relevant to wellbeing as determined by the length of time in any location and by the frequency of

activity in the location. Second, GPS data can be used to assess whether the characteristics of places at specific times contribute to explaining variations in health and wellbeing.

Background

The notion of place in health research is both a spatial unit of analysis and a context that comprises the physical resources, exposures and social relations that may support or weaken health status. As a spatial unit, place is a space with boundaries commonly used for categorizing and discretizing predictors of health status. As context, places can be defined by the significance and meanings people attach to locations where health promoting or health suppressing activities occur. The idea of place as a determinant of health status has recently become a crucial focus of national population health initiatives [1,2]. An increasing number of empirical studies in medical geography and epidemiology have determined that characteristics of place are associated with variations in health-related behaviours and outcomes, even after individual-level attributes and behaviours are taken into account [3-5]. Although statistical associations between characteristics of place and health can be demonstrated, the underlying mechanisms responsible for these relationships remain more elusive. The significant challenges for place-based health research are to ensure that places are accurately represented spatially, and to identify those aspects of context that are related to variations in health and amenable to modification. This study focuses on the more practical issue of spatial bounding as a necessity to operationalize the concept of place. We introduce the development and testing of a wearable global positioning system (GPS) data logger for the purpose of objectively measuring the spatial extent of an individual's location over time. Examination of time-location data allows for inference on the types of activities associated with health status.

There are three principal methods of spatial bounding that dominate the previous literature on place and health research. Most studies make use of existing administrative boundaries, usually created *a priori* by national statistical or postal services. For example, analyses from the United States and Canada usually employ census tracts – small and relatively stable administrative divisions that vary in size by the density of settlement in urban areas [6,7]. Another approach defines places qualitatively according to boundaries and community assets as perceived and defined by their inhabitants [8-10]. More recent studies are defining place according to results derived from manual or automated zoning procedures [11,12]. Place boundaries can be manually determined by statistical design rules to assemble small geographical building blocks into larger regions so as to control population size, or another denominator of interest. Alternatively, basic spatial units can be grouped into larger ones automatically using automated zoning software.

Existing methods of spatial bounding are subject to several limitations. First, the majority of studies assume that the relationships between context and health operate within the confines of a single spatial unit, usually represented by an individual's residential census tract. This assumption may lead to the misclassification of context to variations in health status since it is unlikely that a person would spend all of their time in their residential census tract. Places that influence health are more likely to be spatially interdependent, linked by functional, cognitive and, possibly, sentimental relationships between what happens at one point in space and what happens elsewhere [13]. People live and function in various places that interconnect in complex ways, and to

represent place as a single spatial area risks losing important exposure information.

Second, researchers must ascertain the spatial scale appropriate for analysis, the level of aggregation characteristic to the data available, as well as the appropriate temporal frame within which to study causal relationships. Publicly-available datasets are usually static in space and time, and data are routinely collected without consideration of spatial or dynamic process [14]. Moreover data for health research are limited by lack of attention to spatiality, specifically how the spatial-temporal structuring of daily life defines how social action and relationships are represented [15].

Third, the scale of observation can influence inference [16,17]. This effect is called the "modifiable areal unit problem" and, because changing the shape or size of the units on which data are mapped will change average values of the variables recorded, this can change the resulting correlations or statistical models generated from the data [18]. Spatial units such as postal codes or census tracts may also be changed over time, thereby altering statistical estimates [6,13,19-22]. Several solutions to the problem have been proposed, including statistical bounding [23], multi-scale and zone sensitivity analyses [24], and spatially-weighted regression techniques [25,26].

An alternative approach to delineating spatial boundaries makes use of time-location data. Recording changes in spatial location through time ultimately provides the most complete source of evidence on how place may influence health. All human activities have spatial and temporal dimensions: activities occur at particular places for limited durations [27,28]. By capturing simultaneously the locations and activities individuals through time it is

possible to construct a series of space-time paths that represent objectively both spatial extent and the intensity of activity (as represented by time) in one or more places. Information about time, location and activity is usually acquired from interviews, personal observation (shadowing) or through time-diaries [29]. Other approaches using electronic sensors and loggers have been employed quite successfully in the context of transportation research and time-activity studies [30-33]. Recent efforts have improved on GPS tracking technologies for the purpose of measuring harmful exposures in human health research [34,35]. However, many of these studies have faced limitations in GPS accuracy, battery capacity and data logging memory thus preventing the collection of time-location data over extended periods of time (> 1 week) under a variety of environmental conditions. These limitations also make it difficult to capture individual time-location information in a variety of contexts. The present article describes the development of a new time-location measurement tool suitable for studies where information about location and time is used in predicting variation in human health outcomes.

Global Positioning Systems

In 1995 the US Department of Defence (DOD) developed a satellite-based radio navigation system capable of determining within centimetres a position on the earth's surface. The system consists of 24 active and several "back-up" satellites, that orbit the earth providing all-weather navigation and surveying worldwide [36]. A summary of GPS capabilities is provided here, but for detailed information readers are referred to *Global Positioning System: Theory and Practice* by Hoffman-Wellenhof et al [37].

Global positioning systems (GPS) consist of three components: satellites in space, a ground control system, and the user's instrument. The space component consists of orbiting GPS satellites equipped with atomic clocks, and transmitting two radio frequencies modulated with two types of code: precise and standard. The precise code is reserved for U.S. military operations while the standard code can be used freely by any civilian in possession of a GPS receiver. The civilian code comprises a 50 bs^{-1} radio signal transmitted at 1,575.42 MHz carrying three signals: a pseudo-random code, ephemeris data, and almanac data. Together these provide information on the satellites available for fixing a position, the current time and date, and the approximate constellation of the satellites at any time throughout the day. The ground control segment consists of five monitoring stations, three ground antennas, and a master control station. The monitoring stations passively track all satellites in view and accumulate ranging information. This information is processed at the master control station to determine satellite orbit geometry and to update the navigation message broadcast by each satellite. The user segment of the system consists of GPS receivers that calculate their own distance from each satellite based on the travel time of the pseudo-random sequences encoded into the radio signal. Given the geometric positions of the satellites (their ephemeris), four pseudo-ranges are sufficient to correct clock error and to compute the three dimensional position of the receiver with an average accuracy of approximately 10m [38,39]. Most modern GPS receivers can track 12 or more satellites simultaneously, improving positional accuracy to within 5 m or less.

Natural Resources Canada, a federal government agency, manages a network of ground stations that transmit differential GPS (DGPS) corrections.

These ground stations receive satellite information at a known ground location and estimate the difference between the information received by the satellite receiver and the actual location. Differential-enabled GPS receivers can receive the broadcast DGPS signals from the ground stations and make correction calculations, improving accuracy of position to within 3 m or less. Correction data are also available as public domain information from the Canada-wide differential GPS service, the International GPS Service and the Canadian Coast Guard. GPS signal correction can be performed at the time of measurement, using a DGPS receiver, or data may be post-processed if information on both the position of the DGPS receiver and ground station are collected. Improvements in location accuracy can also be achieved through the reception of signals from wide area augmentation systems (WAAS) and researchers should check to see if this service is available in their geographic region.

GPS signals are not immune to interference. The most severe form can occur from intentional signal degradation, also called "selective availability" by the United States National Space-Based Positioning, Navigation and Timing (PNT) Executive Committee [37]. Intentional, slowly changing random errors could be introduced into the pseudorandom code transmitted by each satellite resulting in substantial reductions in positional accuracy of 50m or more in both the horizontal and vertical directions [40]. However, selective availability was removed from the system under executive order on May 1, 2000. The United States Department of Defence has since declared selective availability will no longer be used based on security concerns.

Several additional sources of interference may introduce errors that limit the usefulness of GPS in some spheres of human health and activity research.

Variability in atmospheric conditions may affect the velocity of GPS signals. In the troposphere water vapour can slow radiofrequency signals resulting in overestimation of signal range. In the ionosphere different components of a signal can be advanced or delayed when interacting with charged gases. The sum of these atmospheric effects can result in errors of 30 to 60 m and vary depending on the angle of inclination of the satellites in view [41]. These effects are greater for satellite signals nearer the horizon where signals travel further through the atmosphere before reaching the GPS receiver.

Of particular interest to human tracking studies are multi-path errors arising from the reflection of satellite signals from other surfaces, including buildings, vegetation, the ground or water. GPS signals are also blocked by materials such as concrete and steel, thus eliminating reception within many institutional and commercial buildings. GPS reception is nonetheless relatively good in automobiles and public transportation vehicles such as buses and trains. GPS accuracy may also be compromised by poor satellite geometry, viewed from the user's location; precision is greatest when signals are received from satellites that are widely dispersed in azimuth and elevation. Thus, two satellites in the same location relative to the antenna provide similar information. The influence of satellite geometry can be quantified using dilution of precision (DOP) indices. Two DOP measures that are important for human tracking research include the positional and horizontal dilution of position (PDOP and HDOP). The first measure expresses uncertainty in overall position, whereas the latter assesses uncertainty on the x and y axes. DOP measures generally range from 1 to 10, so that a location estimated with an HDOP of 2.6

has an uncertainty in the horizontal position that is approximately 2.6 times that of the receiver capability.

Researchers and GPS users interested in minimizing positional errors can undertake a mission planning exercise. GPS satellite orbits are known and predictable so that the number of available satellites and their geometric position can be computed for any location and any time. Mission planning software is freely available, and almanac information can be downloaded electronically in multiple formats. Figure 3.1 is a typical report from mission planning software showing the number of satellites (visibility) and two DOP values (PDOP and HDOP)for 0700 to 2100 hours on September 25, 2007, at an urban location in Halifax, Nova Scotia. The opportunity for best reception is between 0900 and 1630 hours when seven or more satellites are available at most times within this window and PDOP values are less than 2.3.

GPS Applications in Health Research

Advances in the miniaturization of GPS and related technologies have led to an assortment of applications: timing, surveying, logistics, traffic management and control, security, marketing, and navigation systems [42]. Of particular interest here is the development of GPS technology for health-related applications, specifically those concerned with navigation and tracking. Administrators of emergency 911 systems in many larger urban areas use geocoded address and GPS navigation systems to direct emergency response activities. The incorporation of assisted-GPS technology into cellular telephones allows emergency response teams to accurately assess the location of the distressed caller. The U.S. Federal Communications Commission (FCC)

currently requires mobile phone service providers to locate emergency (E911) callers with an accuracy requirement of 100 m (67%) or 300 m (95%) for network-based solutions and 50 m (67%) or 150 m (95%) for handset-based solutions (usually GPS-enabled) [43]. Geocoded emergency 911 databases can be used to identify the location of an individual at a specific time; this information can be linked to contextual data to explore the role of place as a determinant of health emergencies. GPS in conjunction with other technologies has been used to support tuberculosis control programs in South Africa [44,45], and to identify high-risk areas for transmission of vector-borne and environmental diseases [46]. GPS is also used to investigate the positional accuracy of geocoding processing in epidemiological research [47,48]. Finally, microscale positioning systems that use three-dimensional imagery instead of satellite data are showing promise in surgical applications [49].

Although in its infancy, the use of GPS technology for human tracking presents an enormous opportunity for improving understanding of how the characteristics of places and environmental context influence human activity as well as health and well-being. Many technologies and techniques for human tracking have evolved from wildlife tracking research. GPS receivers have been used to track turtles [50], bears and other large mammals [51], farm and pastoral animals [52,53], and primates [54,55] with some success under a variety of landscape conditions. Very light GPS-enabled air pollution sensors have been fastened to homing pigeons in order to send real-time location-based pollutant information to an online database and mapping server (see Pigeonblog.mapyourcity.net).

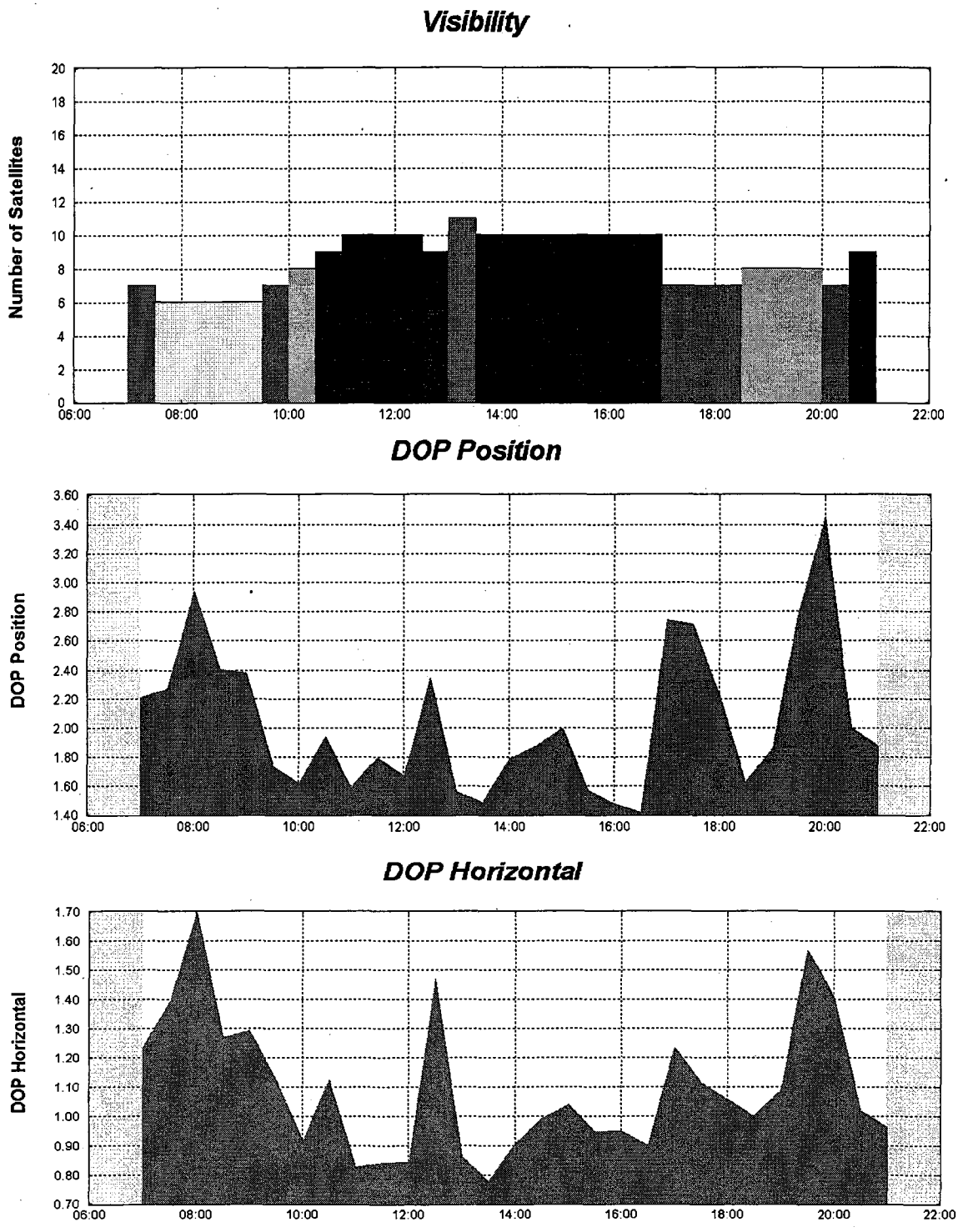

Figure 3.1 *Number of satellites and dilution of position measurements* (PDOP and HDOP) for September 25, 2007, at a central location in urban Halifax, Nova Scotia. DOP values of less than 2 are desirable.

Innovations in GPS technology have cultivated interest in the development of portable and wearable GPS tracking devices for research on human activity. The majority of development in this area has been devoted to the commercialization of technologies for tracking criminals or persons under care of the courts. Titanium ankle bracelets with embedded GPS are routinely used for real-time tracking of prisoner transfers and for monitoring convicted offenders who are subject to restrictions on movement [56]. Several hardware vendors are retailing similar devices to monitor individuals with memory impediments (including Alzheimer's disease), children or individuals at risk of kidnapping, and family pets. Users can establish a "geofence" that generates an alert when a device moves beyond the limits of a predefined geographic boundary.

GPS technology has also been used in studies of physical activity and human exposures. Studies of exercise physiology and nutrition have used lightweight GPS receivers to assess physical activity as measured by the velocity of walking and running [38], to determine the mechanical power of walking [39,57], and to geographically contextualize accelerometry data, which indicates the locations where physical activity occurs [58]. Time diaries play an important role in epidemiological assessment of exposures to hazardous agents present in the environment. Several studies have employed commercially-available or custom designed wearable GPS data loggers to validate time-activity diaries [34,35] or to track individuals in studies of pesticide exposure [59]. More recently, GPS-enabled cell phones have been used to track adolescent travel patterns and activity information [60]. GPS technologies are now being linked with a variety of sensors to investigate relationships between environmental

conditions and human physiology in time and space; these include sensors of environmental factors such as carbon monoxide concentrations or air temperature, and health-related factors such as heart rate [61,62].

The purpose of this study is to develop and pilot test a customized wearable GPS data logger suitable for tracking human subjects over lengthy periods of time. The ability to track people over extended periods of time facilitates the development of individualized spatial units for place and health analyses. In more urbanized areas the application of GPS technology to accurately measure location over time requires evaluative pilot testing for reliability and validity to ensure feasibility of the technology under actual conditions. Here we propose a general framework of dynamic and static tests for evaluating and testing human tracking devices based on GPS technology. A novel contribution of this work is the testing of a wearable GPS across multiple modalities of dynamic measurement among a variety of urban contexts. Knowledge of time-location patterns plays a critical role in understanding how people interact with, and use, space, and reveals the 'places' relevant to the study of variations in health outcomes.

Methods

Development of a Wearable GPS Data Logger

Technological features relevant to the development of wearable GPS for exposure assessment research have been discussed elsewhere [35,59]. The following list incorporates features from previous work, and introduces several additional physical and performance-based features judged to be critical for human tracking studies: a) size and weight (relatively light and unobtrusive,

<0.5kg), b) logging capability (configurable logging frequency and adequate data storage), c) run-time (minimum 2 d battery capacity at frequent sampling intervals, quick recharge), d) passive (simple to operate and requiring little or no interaction during logging), e) durable (resistant to vibration, minor impacts and water resistant), f) fast time-to-first-fix (obtain fix quickly after signal loss), g) accurate (2-5m resolution) and precise among a variety of built and natural environments).

After constructing several prototypes we developed a wearable GPS data logger instrument called the HeraLogger. The HeraLogger comprises a PVC case (165 mm x 71 mm x 25 mm) containing the GPS module, data logger and battery pack, and an external magnetic patch antenna (Figure 3.2). The instrument weighs approximately 170 g and easily fits into a jacket pocket or small bag. The antenna has a 2 m cable and can be positioned appropriately to maximize visibility of the sky and satellite signal reception. The GPS module can be configured to output position information at sampling rates up to a maximum of four times per second; data are logged to a removable SD card with capacity up to 1 GB. The instrument can accommodate multiple battery capacities, ranging from 2.4 Ah to 10.4 Ah; this range corresponds to 16 h to 71 h of runtime, or 57 600 to 248 400 data points using a one per second sampling rate. An on/off switch initiates the logging of geographic position and the instrument can be left on while recharging the batteries. The GPS module is a 16-channel receiver with a rated time-to-first-fix of less than 34 s for a cold start, less than 3.5 s for a hot start, and is accurate to within 2 to 5 m of its actual position [63]. Software was developed to read, parse and write satellite data to a text file suitable for import into a geographic information system or

statistical software package. The cost of each instrument is approximately $450 not including labour costs associated with assembly. Four GPS instruments were assembled for further testing.

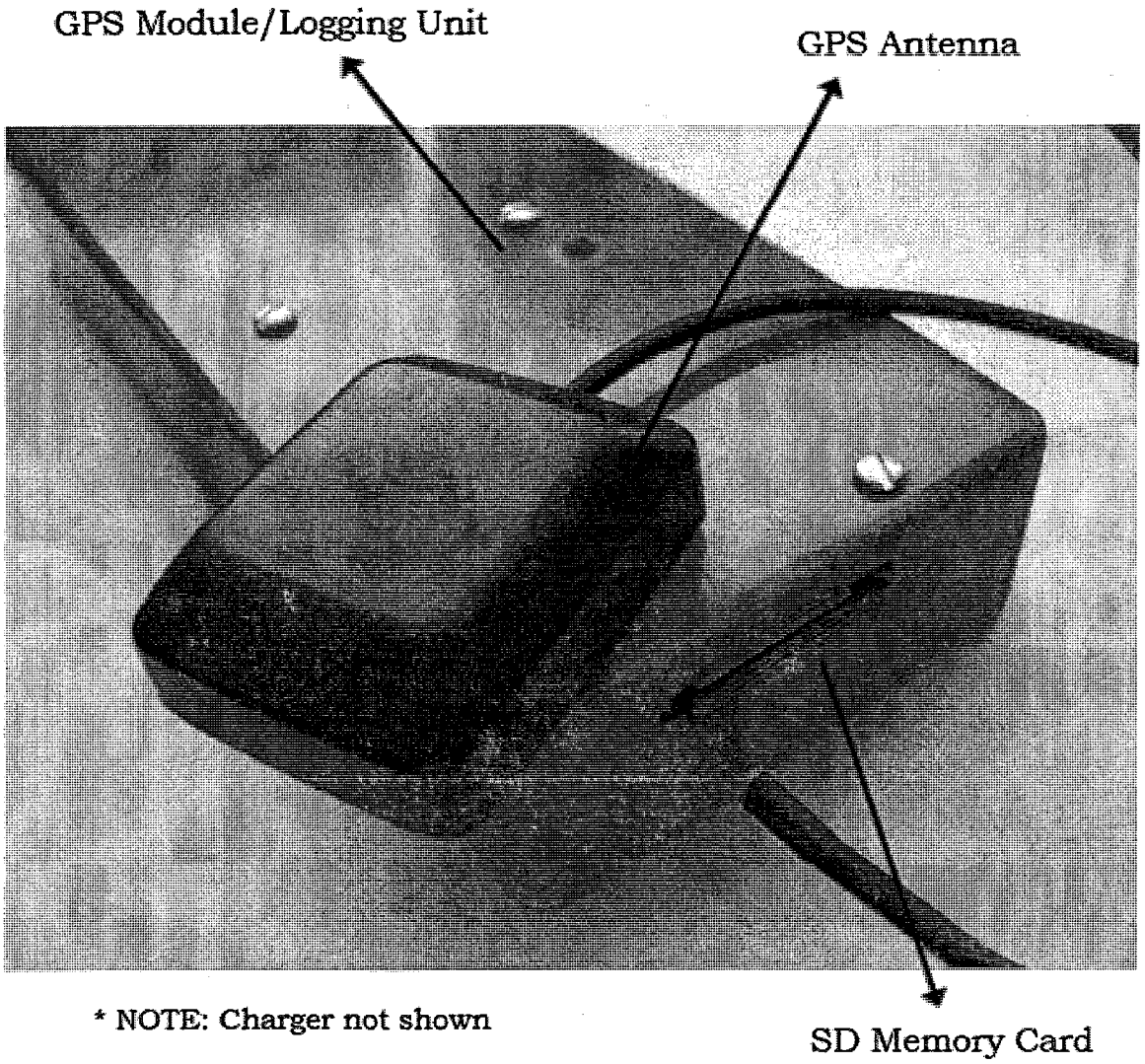

Figure 3.2 *The HeraLogger.* A wearable GPS data logger suitable for health and place research.

Static Tests

Static testing of the Heraloggers was conducted during the summer of 2007 at Dalhousie University, Point Pleasant Park and at the Art Gallery of

Nova Scotia in Halifax, Nova Scotia. Three static tests were performed to assess instrument accuracy and precision under field conditions commonly experienced by human subjects. These conditions included the edge of an urban forested park (some obstruction from trees), an open rooftop with no obstructions, and near a building wall to simulate urban canyon conditions (Figure 3.3). GPS performance improves as the percentage of open sky increases [36].

Precision was estimated for all three sites; accuracy was assessed only at the park location using a known geodetic location, in this case a municipal survey monument maintained by the Province of Nova Scotia (Northing: 4940643.46, Easting: 454981.21, NAD83, UTM Zone 20N). The four instruments were assessed simultaneously to control for the effects of weather (atmospheric interference) and variations in position estimation resulting from dilution of position (DOP). DOP refers to the geometric strength of satellite configuration on GPS accuracy [37]. None of the logged synchronous data were filtered for GPS signal quality so as to simulate actual field conditions. Sampling periods were not selected for optimal signal reception.

Urban Park Static Testing

The antenna from each GPS instrument was placed as close to the geodetic point as possible. The potential for inter-instrument interference was negligible given the use of passive antennas on each GPS device. Data were collected at 5 s intervals for a 1 h period resulting in a total of 720 data points per instrument for analysis. The average of all logged coordinates was compared with the known geodetic point to obtain an estimate of the accuracy of each

instrument and to evaluate the total mean error from all four instruments. An additional test was performed to evaluate instrument precision. Data were collected at 5 s intervals for a 2 h period in a location in close proximity to the geodetic reference position. Precision was measured in terms of the standard deviation of the measured coordinates for each instrument.

Rooftop Static Testing

To evaluate the static performance of the GPS instruments under open sky conditions, four instruments were placed in watertight containers and positioned in a random formation (with a minimum distance between instruments of 1m) on the rooftop of a building (Northing: 4943129.5, Easting: 453208.7, NAD83, UTM Zone 20N) at Dalhousie University. An effort was made to select a rooftop of sufficient elevation to prevent interference of satellite signals (multipath errors) from adjacent structures. GPS data were collected over a 24 h period.

Urban Canyon Static Testing

To assess the impact of multipath errors arising from the influence of tall buildings characteristic of dense urban development (also known as the urban canyon effect), GPS instruments were placed at 1 m intervals in a straight line perpendicular to the outside wall of an eight story building (Northing: 4944229.0, Easting: 454802.6, NAD83, UTM Zone 20N) in downtown Halifax. We hypothesize signal reception should worsen under 'urban canyon' conditions where the potential for multipath errors due to building interference increases. Data were again collected at 5 s intervals for a 1 h period.

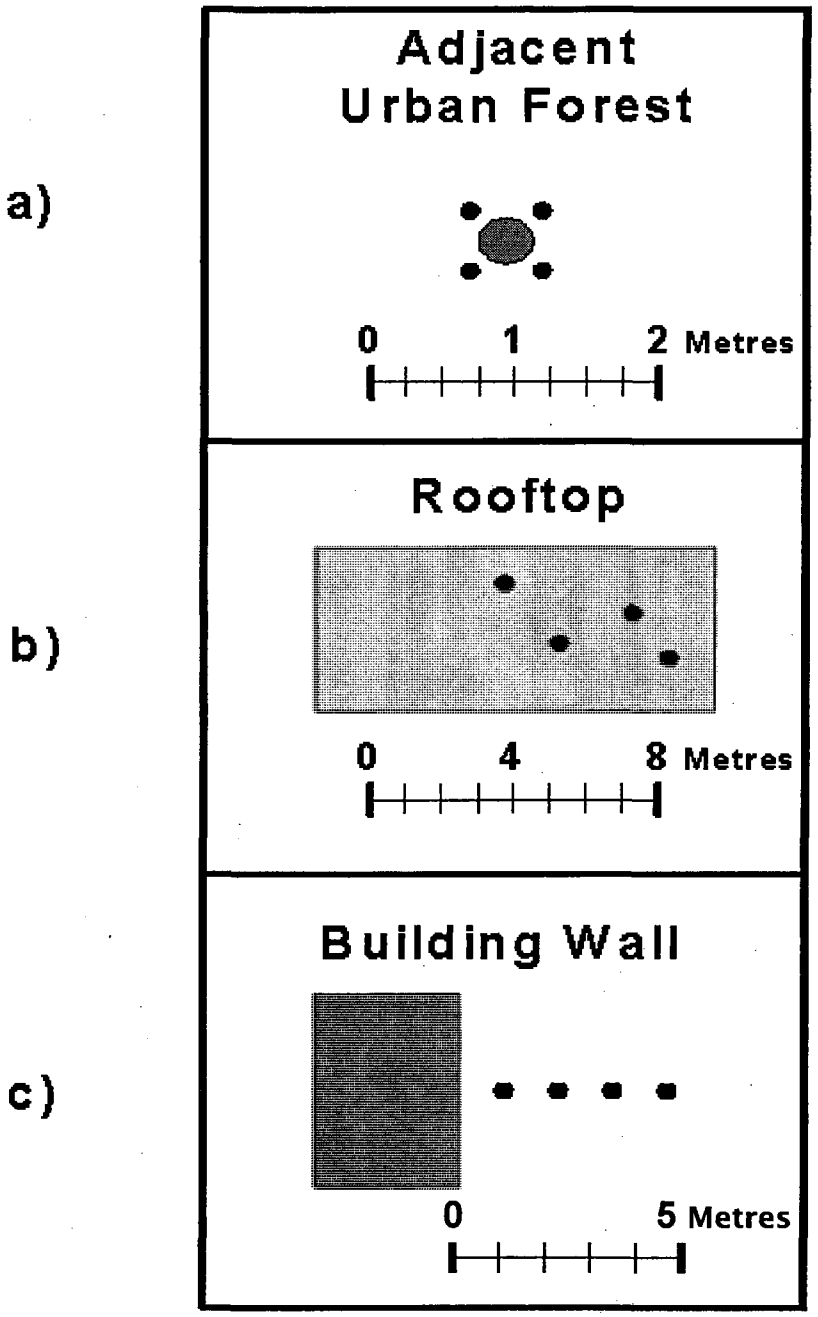

Figure 3.3 *Configuration of GPS instruments for static testing*: a) positioned adjacent to a survey monument; b) various rooftop locations at least 1 m apart; c) perpendicular to building wall at 1 m increments.

Static Testing Analysis

Accuracy and precision based on the static tests were evaluated according to guidelines established by the Institute of Navigation and U.S. Department of Defence GPS specification documents [64,65]. Since the tracking of human movement focuses on the location of an individual at a point in time, only the horizontal accuracy and precision of the GPS instruments were calculated. All logged coordinates were converted from WGS-1984 geographic coordinates to UTM Cartesian coordinates (UTM, NAD83, Zone 20N). The current version of WGS-1984 and the North American Datum of 1983 are equivalent; however, we note that the native instrumentation of the GPS system determines coordinates within the WGS-1984 reference system and thus, and transformations should be done in post-processing. The difference in horizontal accuracy and precision was calculated using equation 1:

$$\Delta H = \left(\Delta e^2 + \Delta n^2\right)^{\frac{1}{2}}, \qquad (1)$$

where Δe is the change in longitude [easting], and Δn is the change in latitude [northing]. In both directions the change is dependent on a reference location. GPS instrument accuracy measures were derived from the forested park static test with the average of each instrument's logged coordinates compared to a known geodetic point. Precision measures were calculated using average of all logged points for each GPS instrument as the reference location so that coordinate point was compared to the mean of all logged coordinates. We assumed a Gaussian error distribution for measurements of latitude and longitude, which has been shown to be representative of coordinate measurements based on stand-alone GPS receivers [66]. The calculated

difference values [ΔH] for each GPS instrument were ranked in order to apply the most common methods of comparing GPS accuracy, based on the circular error probable [CEP], horizontal accuracy distributions, and standard deviations in the x and y directions for each instrument [67,68]. CEP is the radius of a circle, centred at the antenna position, containing 50 percent of the points around the average value of all measurements [69]. Horizontal accuracy distributions were calculated as the radii of two circles, centred at the antenna position, containing 95 and 98 percent of all GPS points logged. S-plus statistical software was used for all calculations (S-Plus for Windows, Seattle, WA).

Dynamic Tests

Positional data from each of the four GPS instruments were collected for four transportation modes: walking, cycling, automobile, and transit bus. Walking and cycling data were collected along a route approximately 5km in length. The average time to complete the route was 66 min for walking and 24 min by bicycle. Test participants were asked to walk in the middle of the sidewalk, unless passing another pedestrian, and while cycling to maintain a consistent distance away from the curb unless changing lanes or turning. The automobile test route was approximately 40 min in length; drivers were instructed to abide by posted speed limits and to select the lane closest to the curb on roads with more than two lanes. Transit bus data were collected along an urban downtown bus route with a total loop time of approximately 80 min. Riders were not provided with any specific instructions regarding seating

placement in order to avoid special efforts to improve signal reception by selecting a window seat.

Dynamic Testing Analysis

All positional data were converted into Cartesian coordinates and imported into a geographic information system for further analysis. Digitally orthorectified aerial photographs [70] were used to determine the true path coordinates by creating polyline themes for each transport mode route. True paths were in the middle of the sidewalk for the pedestrian data, within 1m of the curb for cycling data, and in the middle of the lane for automobile data (except when lanes were crossed for turning). A similar process was used for the bus route, using spatially-referenced route data supplied by Halifax Regional Municipality served as a guide. Variations in the widths of the sidewalks and roads were accounted for when determining the true path polylines. GPS data from each transportation scenario were categorized according to three types of built environment: mixed density, open sky, and urban canyon. The route of the transit bus did not allow for the collection of GPS data under open sky conditions. Buffers of 2, 3.5, and 5 m were created on either side of the true paths and coordinates were analyzed to determine the percentage of points recorded inside each buffer distance and in each built environment type (Figure 3.4). The numbers of satellites used to determine location and dilution of position measures (HDOP and PDOP) were recorded directly from GPS output.

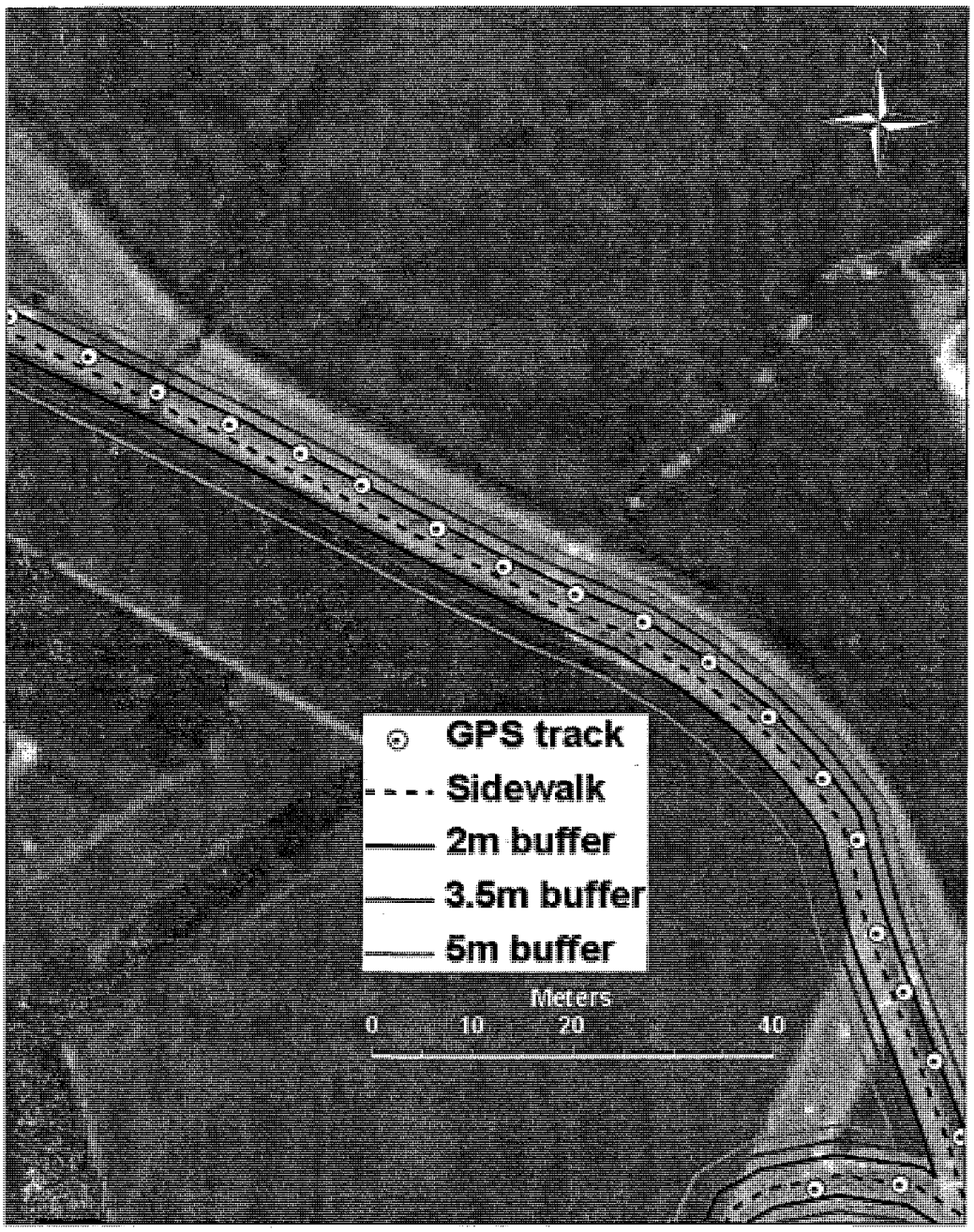

Figure 3.4 *A sample of points (⊙) logged by the GPS instrument during a 45 minute walking test under optimal reception conditions.* The true path (dashed line) is the sidewalk. Most points fall within 2m of the true path.

Results

Static Tests

Table 3.1 shows the number of points logged by each HeraLogger to determine the accuracy of the instruments. The average duration of the test was 68 min. The loggers received information from an average of 10.3 satellites during the course of this evaluation resulting in accurate position estimates and nominal PDOP and HDOP values (i.e. below 4.0 and 2.0 respectively). Results revealed horizontal position accuracies of 2.65 ± 0.25 m for 50 % of logged values, 7.83 ± 1.17 m for 98 % of logged values, and an average distance of 2.82 ± 0.40 m away from the known reference location.

Table 3.2 gives details of the precision of the GPS instrument under three built environment scenarios. Precision was best in the park setting. The average duration of the logs was 115 min, and the mean number of satellites obtained, as well as HDOP and PDOP values, were similar to those data from the accuracy tests. Half of the values lie within 2.00 ± 0.35 m and 98 % lie within 5.45 ± 1.06 m. Logged data from the rooftop location are to some extent less precise than those from the urban park location. Logging took place over a 24 h period and, on average, one less satellite was used to provide a location solution. The mean CEP value is 2.35 ± 0.11 m and 98 % of the location data fall within 6.18 ± 0.29 m. Position precision estimates worsened under urban canyon conditions where multipath effects are expected to be more of an issue. Data were logged on average for 63 min; three fewer satellites were available to derive location solutions, in comparison with the urban park test. PDOP values almost doubled compared to other locations. The radius of the circle required to capture 50 % of the position data was roughly nine times larger than for data

Table 3.1
Horizontal accuracy comparison of four GPS instruments from the Forested Park test

Logger	N	Satellites[a]	HDOP[a]	PDOP[a]	Accuracy Description			
					CEP[a]	H95[a]	H98[a]	Distance[b]
6	825	10.3	1.19	1.90	2.60	5.00	8.00	3.33
14	819	9.9	1.44	2.34	3.00	6.00	7.20	3.00
15	814	10.4	1.37	2.03	2.60	6.90	9.40	2.49
23	811	10.4	1.17	2.06	2.40	5.60	6.70	2.53
Mean±SD[c]	817	10.3±0.23	1.29±0.13	2.08±0.18	2.65±0.25	5.88±0.79	7.83±1.17	2.82±0.40

[a] HDOP = horizontal dilution of position; PDOP = positional dilution of position; CEP = circular error probable (50%); H95 and H98 = horizontal accuracy distribution at the 95 and 95 percent levels. All are averaged values.
[b] Distance in metres between geodetic reference point and average of all recorded GPS data.
[c] Standard deviation

Table 3.2
Horizontal accuracy estimates of four GPS instruments in three built environment types

GPS ID	N	Satellites[a]	HDOP[a]	PDOP[a]	Accuracy Description CEP[a]	H95[a]	H98[a]
Urban Park							
6	1371	10.3	1.00	1.87	1.40	3.30	4.00
14	1398	10.3	1.00	1.83	2.20	4.40	4.90
15	1380	10.4	1.03	1.89	2.30	4.90	6.20
23	1374	10.3	1.06	1.93	2.10	5.00	6.70
Mean±SD[c]	1380	10.3±0.0	1.02±0.02	1.88±0.04	2.00±0.35	4.40±0.67	5.45±1.06
Rooftop							
6	17284	9.9	1.07	1.89	2.50	5.10	5.90
14	17947	9.4	1.10	1.85	2.20	5.00	5.90
15	17946	9.2	1.09	1.87	2.30	5.20	6.30
23	17944	9.3	1.06	1.82	2.40	5.60	6.60
Mean±SD[c]	17780	9.4±0.3	1.08±0.02	1.86±0.03	2.35±0.11	5.23±0.23	6.18±0.29
Urban Canyon – Wall Test							
1	762	7.2	1.43	3.53	11.40	48.00	69.10
2	770	7.3	1.40	2.81	20.10	24.60	24.60
6	755	7.7	1.49	2.95	9.50	57.90	78.00
15	774	7.5	1.43	2.96	13.40	34.10	39.10
Mean±SD[c]	764	7.3±0.2	1.49±0.04	3.16±0.32	14.04±4.62	43.46±14.73	53.14±25.06

[a] HDOP = horizontal dilution of position; PDOP = positional dilution of position; CEP = circular error probable (50%); H95 and H98 = horizontal accuracy distribution at the 95 and 98 percent levels. All are averaged values.
[b] Distance in metres between geodetic reference point and average of all recorded GPS data.
[c] SD = Standard deviation

from the urban park. A circle with an average of radius of 53.14 ± 25.06 m captured up to 98 % of the GPS data.

Dynamic Tests

Table 3.3 shows the performance of the GPS instruments using different forms of transportation in the three built environments. Positional accuracy under open sky conditions was best when cycling and walking (72 % to 99.1 % of all positions within 5 m). No data are available for transit bus tests in open sky conditions. In mixed density areas, determinations of position were more accurate from automobile logs (89 % within 5 m), followed by cycling (81 % within 5 m), walking (74.5 % within 5 m) and then transit bus (65 % within 5 m). In urban canyon areas where GPS receivers are most challenged, the greatest positional accuracy was attained from automobile (82.6 % within 5 m) and transit bus modes (60.2 % within 5 m), followed by walking and then cycling (57 % and 53.7 % within 5 m, respectively).

Satellite reception was best for automobile travel (10 satellites) followed by walking, cycling and then transit bus transportation (8.3 satellites); however, this difference in reception did not always translate into reduced horizontal and positional dilution of position values. Figure 3.4 shows a close-up perspective of a pedestrian path under open sky conditions. The dotted line shows the true path (sidewalk) bounded by 2 m, 3.5 m, and 5 m buffers, as well as the actual GPS locations logged at 5 s intervals. As expected, signal accuracy for walking and cycling deteriorated as the potential for the built environment to interfere with satellite reception increased. Differences in signal reception are less apparent under varying built environments for automobile trips.

Table 3.3
Resolution estimates of four GPS instruments derived from four transportation modes among three built environment types

GPS ID	N	Sats	HDOP	PDOP	Fraction of points within each buffer (%)											
					Mixed Density				Open Sky				Urban Canyon			
					N	±5 m	±3.5 m	±2 m	N	±5 m	±3.5 m	±2 m	N	±5 m	±3.5 m	±2 m
Walking Tests																
6	824	8.9	1.47	3.08	419	91.4	78.5	53.0	189	100.0	98.9	85.7	216	71.3	64.8	52.8
14	821	8.6	1.96	2.70	412	52.4	40.8	27.4	203	95.1	82.8	53.2	206	43.2	35.9	20.9
15	702	9.9	1.43	2.87	355	84.5	73.0	53.8	167	98.8	97.6	87.4	180	62.2	56.1	43.3
23	826	9.1	1.51	3.02	418	87.1	80.1	61.5	189	98.9	94.2	81.0	219	61.2	56.6	41.1
Mean	800	9.2	1.68	2.88	403	74.5	63.2	44.5	190	96.9	90.8	72.0	206	57.0	49.2	35.0
Bicycle Tests																
6	294	8.7	1.58	2.61	140	90.0	74.3	47.9	81	100.0	97.5	76.5	73	50.7	34.2	16.4
14	297	9.1	1.52	2.49	141	73.8	58.2	38.3	80	98.8	97.5	87.5	76	53.9	43.4	30.3
15	296	8.2	1.61	2.66	135	78.5	65.9	41.5	81	98.8	91.4	64.2	76	60.5	42.1	25.0
23	293	8.4	1.55	2.53	139	82.0	61.2	38.1	82	98.8	90.2	70.7	72	50.0	41.6	20.8
Mean	295	8.6	1.57	2.57	138	81.0	64.9	41.4	81	99.1	94.1	74.7	74	53.7	40.3	23.1
Automobile Tests																
6	454	10.1	1.28	2.69	296	94.3	87.5	69.6	63	92.1	76.2	49.2	95	83.2	69.5	60.0
14	454	9.9	1.27	2.65	296	94.9	83.1	63.9	63	92.1	82.5	55.6	95	84.2	72.6	53.7
15	452	10.1	1.25	2.56	294	78.6	70.1	51.7	63	92.1	82.5	61.9	95	77.9	75.8	58.9
23	454	10.1	1.25	2.59	296	88.2	80.1	56.4	63	92.1	81.0	57.1	95	85.3	74.7	54.7
Mean	454	10.0	1.26	2.62	295	89.0	80.2	60.4	63	92.1	80.5	55.9	95	82.6	73.1	56.8
Transit Bus Tests																
6	1076	9.7	1.45	2.46	827	72.8	58.4	37.2					249	73.1	57.0	36.1
14	885	8.8	1.52	2.57	618	60.0	43.9	23.3					267	64.4	50.2	27.3
15	767	7.5	1.31	2.16	552	69.4	55.1	36.2					215	61.9	47.4	31.2
23	929	7.2	1.34	2.24	725	70.5	55.3	37.2					204	62.3	44.6	27.0
Mean	918	8.3	1.41	2.37	680	65.0	50.3	31.6					237	60.2	45.8	28.1

Figure 3.5 shows the relationship between horizontal (HDOP) and positional dilution of position (PDOP) under static and dynamic GPS instrument testing conditions. Static HDOP varies in a log-linear fashion with PDOP, so that reductions in horizontal accuracy diminish at a value of approximately PDOP = 2.3; this implicates vertical dilution of position as the reason for decreased PDOP in static conditions. PDOP varied less with HDOP under dynamic conditions with no clear association between dilution of position values. HDOP values were greater under dynamic as compared to static conditions.

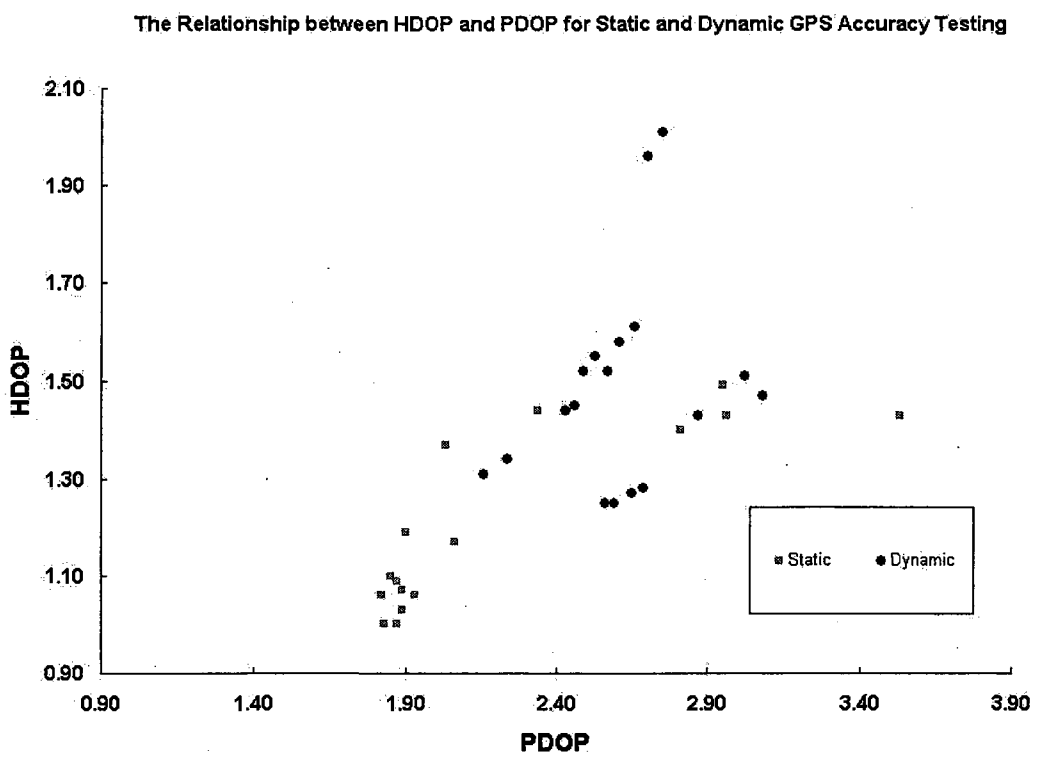

Figure 3.5 *The relationship between HDOP and PDOP in static and dynamic accuracy testing conditions.* Dilution of position increases under dynamic conditions.

Discussion

Finding an approach to accurately define living spaces is a problem inherent to place and health research. Because of the way existing data are presented, researchers are usually forced to adopt existing administrative boundaries; if these are inadequate they may have to develop alternative strategies to relate characteristics of place to explanations of health variations. Wearable global positioning systems (GPS) can accurately describe where individuals spend their time thus providing a more detailed assessment of places relevant to health. GPS data are also preferred to the use of time diaries as they minimize recall bias and may also reduce problems of compliance [34].

The objectives of this research were to develop and pilot test a wearable GPS instrument for health and place research, as well as to establish a general framework of dynamic and static tests for evaluating and testing human tracking devices based on GPS technology. Specifically, we developed a passive wearable GPS receiver data logger that provided consistent time-location recording capabilities under a variety of static and dynamic conditions in an urban environment. Unlike devices used in previous research, the design characteristics of our GPS instrument allow for extended high resolution positioning under typical urban conditions and required little input or maintenance. The instrument can sample at 1 s intervals for approximately 70 h continuously before recharge, and there is no danger of approaching data storage limitations. Comparison with devices used in other studies is difficult due to the range of parameters selected by researchers, as well as a determination of what constitutes a "wearable" device. However, a similar device

designed for assessing human exposures was able to record 25 h of data at 5 s intervals, and had a maximum logging capacity of 30 h [59].

Position accuracy and instrument precision under static and dynamic conditions in a variety of environments is critical for time-location analysis. There are a number of factors that influence GPS instrument position accuracy, most of which are unavoidable or beyond the control of the researcher; however, the influence of these factors is usually measurable. For example, researchers can investigate satellite constellation geometry to choose sampling times when dilution of position is diminished. Errors may also arise from atmospheric interference and instrument quality. Due to cost restrictions most survey-grade GPS (highly accurate) are not amenable to human tracking studies at this time.

The average accuracy of our GPS instrument is 2.8 m (±0.4 m) when not in motion. This is a respectable degree of accuracy when compared to a range of 1.7 m to 10 m reported in similar studies [35,53,59,71], and is likely to be acceptable for most place and health studies. Instrument precision did not vary much between open and mixed density urban development conditions (98 % of values lying within 5.5 m to 6.2 m of the true location). However, accuracy fell sharply in urban canyon settings (98 % of values within 53.1 m of the true position). These values, which are similar to those obtained in similar evaluations [72], would inflate in larger cities with taller buildings and denser development.

GPS instrument accuracy under dynamic conditions is particularly relevant for place and health research, as well as for exposure assessment studies. People infrequently remain in one location for extended periods of time (for more than 3 hours with the exception of sleeping), and movement will occur

among a variety of locations and encompass multiple transportation modes. We evaluated the accuracy of a wearable GPS instrument in three types of urban environment across four transportation modalities. As expected, instrument accuracy is greatest when the potential for interference is least, regardless of transportation mode. However, the impact of the environment was less pronounced for automobile and bus transit modes, with the latter mode having relatively poorer absolute accuracy, regardless of location in an urban area. We found that under dynamic conditions, positional accuracy tends to improve as the distance from potential interference increases. Automobiles and buses operate in roadways which are further from buildings and other objects than cyclists or pedestrians. In a study involving children from the Seattle area, two wearable GPS instruments were tested for position accuracy after a 4 km walk in the city. The researchers reported 96 percent of locations within 5 m and 78.8 % within 2 m [59] compared to 76.2 % and 50.5 % from our tests. However, direct comparison is difficult since the instruments used in the Seattle study were switched on in advance of data collection (this ensures a good initial location fix), and the data were post-processed to correct for errors using differential signal data. No information about the potential for physical interference arising from urban structures and features was available in that study.

The wearable GPS instrument described here is sufficiently accurate to locate and correctly classify a variety of human activities. Ideally, position data would be obtained for all activities regardless of environment. However buildings constructed of impenetrable materials limit GPS tracking. Although we do not report on measurements undertaken indoors, preliminary data from

an unpublished pilot study of 53 individuals suggests that indoor tracking is possible under some conditions. The inconsistency of reception indoors, and to some extent outdoors, is explained by building materials, proximity to windows or sky, distance from building walls, and potential interference from other electronic devices [73]. Specifically, indoor environments reduce satellite availability, accuracy (due to high noise and degraded geometry), positioning continuity, and reliability. The availability of high-sensitivity GPS (HSGPS) and assisted GPS (AGPS) will help to improve indoor positioning performance [74]; however, even under ideal indoor conditions, signal accuracy is limited to within 10m for residential and 70m for commercial buildings [43].

Clearly GPS tells us very little about the context of place or the places where activities occur. While the data may indicate a visit to a local pub, we have no qualitative information on whether the visit was a pleasant experience or not. Ultimately combining GPS position data with questionnaires, interviews or other forms of data collection would enhance our understanding of place and how it influences health and well-being.

A wearable GPS instrument such as the HeraLogger could be used in other health research settings, and may be able to provide novel insights into temporal and spatial processes underlying place and health associations. We have conducted a pilot project where GPS instruments were worn with passive air particle samplers to improve air pollution exposure assessments. Collecting GPS position information over a 7 d period provides a crude but objective estimation of an individual's spatial footprint. In future work we intend to compare this footprint to boundaries traditionally used in place and health research to assess bias arising from misclassification of place. Also of interest is

the development of measures created from GPS information relevant to processes associated with variations in health. For example, social capital researchers may find GPS data useful for investigating places where socialization does and does not occur outside of the home and work environments. What is apparent from the data we have collected to date is that GPS data and time-location analysis will enable a more appropriate characterization of human activity patterns, so that we may better comprehend the spatial and temporal processes underlying the determinants of population health.

Conclusion

Wearable GPS instruments can monitor human activities. Spatial accuracy is adequate to locate individuals within distinct sub-environments and, with knowledge of location, it is possible to make some assumptions about activity. Rather than rely on static areal units as proxies for places, wearable GPS devices can be used to derive a more complete picture of the different places that influence an individual's well-being. The data are objective and less subject to biases associated with recall of location. The resulting information can be visualized using maps delineating the spatial and temporal boundaries traversed by individuals. This is important for two reasons. First, it brings a dynamic perspective to place and health research. The influence of place on health is dynamic in that certain places are more or less relevant to wellbeing determined by the length of time in any location and by the frequency of activity in the location. Second, data can be grouped by traditional health determinants to ascertain if there are any consistent spatio-temporal patterns among groups

with similar characteristics, and whether there are characteristics of places in time that comprise or can explain variation in health and wellbeing as distinct from social and economic health determinants. Overall, the use of wearable GPS-enabled technologies represents a logical next step in the examination of the association between place and health.

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Chapter 4

A Healthscapes Approach to Operationalizing Context for Place and Health Research

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What is already known on this topic?

- Much context and health research is reliant on conventional and static representations of space and place.
- It is necessary to define in an empirical fashion the spatial unit(s) in which it is postulated that relevant contextual "exposures" occur.
- Contexts operationalized using census geography will be less salient for individuals whose routine activities do occur close to home.

What this study adds:

- Global positioning system (GPS) technology is useful for providing the necessary space-time activity information for the construction of spatial boundaries (healthscapes).
- More than 30% of individual activities take place outside of the residential census tract.
- The spatial extent of an individual's healthscape is moderately related to physical health, age, employment status and household income.
- Although the collection of high resolution time-location data is not feasible for every study, there is no reason why future studies of context and health cannot take into account, even in a small way, the locations where activities occur that may or may not be associated with health.

Introduction

Researchers and policy makers have recently focused their attention on how contexts influence health. This focus centres around understanding how features of place are associated with health outcomes, either independently, or in combination with attributes of the people who live there. A number of studies and reviews have shown convincingly that contextual characteristics are related to a variety of health states and their determinants, including mental health, obesity, health care utilization, physical and social activities, as well as risk taking behaviours such as smoking, alcohol consumption, and gambling (Arcury et al., 2005; Diez Roux, 2002; Ellaway and Macintyre, 2004; Popay et al., 2003; Robert, 1999; Sampson, 2003; van Lenthe and Mackenbach, 2002; Wainwright and Surtees, 2004; Wilson et al., 2006; Yen and Kaplan, 1998). And yet, we still do not have a firm grasp of which aspects of context affect health. Identifying the mechanisms and empirical evidence to substantiate a contextual effect on health would make a valuable contribution towards the development of policy initiatives and interventions aimed to improve health by increasing the salutogenic properties of places (CIHI, 2005; Diez Roux, 2004; Macintyre et al., 2002).

Although a significant amount of empirical research demonstrates a contextual effect on the health of populations, the characteristics of context are by and large not well conceptualized. Indeed, several commentaries on the contextual effects literature are critical of the data sets used, the research methods employed, as well as the predictive value of context in explaining variations in health (Gephart, 1997; Messer, 2007; Mitchell et al., 2000; Pickett and Pearl, 2001). Some of this criticism is addressed with the development of

multidimensional and relational frameworks for conceptualizing and measuring contextual influences on health (Cummins et al., 2007; Galster, 2001; Macintyre et al., 2002). These frameworks provide a useful basis for exploring the links between concepts of context and their measurement, and suggest viable approaches to strengthening empirical studies of context and health. Nonetheless, much contextual research is still reliant on conventional and static representations of space and place (Smith and Easterlow, 2005), and offers little guidance on the partitioning of geography relevant to specific contextual conditions and to specific health outcomes.

The present research is based on an original quantitative data set that enables exploration of the true contexts of people, and how these contexts are associated with health and its determinants. The study combines data from a novel wearable global positioning system data logger, and data from a written questionnaire administered to a random sample of residents in a medium-sized Canadian city. Specifically, it explores the differences between characteristics of conventional geographic boundaries such as census tracts constructed for administrative purposes and boundaries of an individual's healthscape. In doing so, this work represents an attempt to explore associations between predictors of health and health outcomes using contextual data derived from objectively measured spatial units.

A 'healthscape' is an alternative representation of context relevant to health and well-being. The goal of the present analysis is to advance methods for evaluating contextual exposures and the mechanisms linking context to health. To date, insufficient attention has been paid to assessing the soundness of census tracts, or other administrative spatial units, for studying associations

between context and health. In this investigation we compare the morphological, compositional, and contextual properties of census tracts to spatial units as defined by spatial and temporal characteristics of peoples' activities. These healthscapes, developed through the novel use of global positioning system (GPS) technology, geographic information systems (GIS) and theories from spatial ecology, endeavour to overcome the conceptual and logistical challenges faced by previous studies of context and health.

Bounding Context

The strength of contextual effects on health change according to the characteristics of the spatial unit selected (Flowerdrew et al., 2008; Krieger et al., 2002; Oliver and Hayes, 2007; Reijneveld et al., 2000). Thus it is necessary to define in an empirical fashion the spatial unit(s) in which it is hypothesized that relevant contextual "exposures" occur. In conventional studies, the residential locations of persons in a population under study are geocoded and mapped to one or more spatial units, usually census tracts, wards, or other neighbourhood level equivalents. Place of residence is used as the basis for spatial boundary selection so that characteristics of the residential census geography is in effect used as a surrogate for context.

There are good reasons for using existing spatial units such as census tracts for context and health research. First, analysts are relieved of the necessity to develop their own geographic boundaries. Second, these spatial units are easily linked to census and other survey data useful for measuring the contextual environment. Third, the relative stability of census geography over time affords an opportunity to undertake longitudinal or cohort studies (Curtis

et al., 2004), although the composition of the population may change markedly over the same period.

On the other hand, using administrative spatial units may not accurately capture the dimensions of context or the geographies of everyday life relevant to health. A problem that has been long recognized by health geographers is there are no clear boundaries to the contexts that influence health. Definitions of neighbourhood and the contexts of everyday life vary considerably among people (Coulton et al., 2001; Lee and Campbell, 1997). Basing analyses on census tract boundaries assumes that the only contexts relevant to health exist within a short distance from residential location. However, the effects of context on health depend on how much a person is "exposed" to where they live (Sastry et al., 2002). Context operationalized using census geography will be less salient for people whose routine daily activities (including employment, social, and physical activities) do not occur close to home. Thus, researchers run the risk of divorcing geographic space from social space (Gatrell, 1997), and jeopardize the opportunity to consider the spatial and dynamic processes characteristic of life.

The influence of context on health is also likely to vary according to a person's position in the lifecourse. The quality of context early in the lifecourse has a significant effect on health outcomes later in life (Curtis et al., 2004). As children develop into adolescence the importance of social and physical contexts close to home are diminished (Larson et al., 2001), mobility and independence increase, and ties with people external to residential context become stronger (Schiavo, 1988). Figure 4.1 provides a hypothetical representation of how the area of contextual influence varies over the lifecourse.

The trend of increasing mobility and contextual extent carries into adulthood until the dissolution of the family "unit" and subsequent return to stronger attachments with local contexts as aging occurs. Ultimately, the bounding of context raises concern about construct validity, or the degree to which inferences about context and health can legitimately be made with context spatially limited to census geography. For example, contextual measures derived from census level information may have less error for individuals whose residence is in the center of the boundary than along its edge. Further measurement error arises as the number of activities outside the boundary increase. Rarely do studies of context and health evaluate the level of bias introduced when misclassifying context in relation to health outcomes. Resolution of these issues will require approaches that describe human activity in geographical and social contexts.

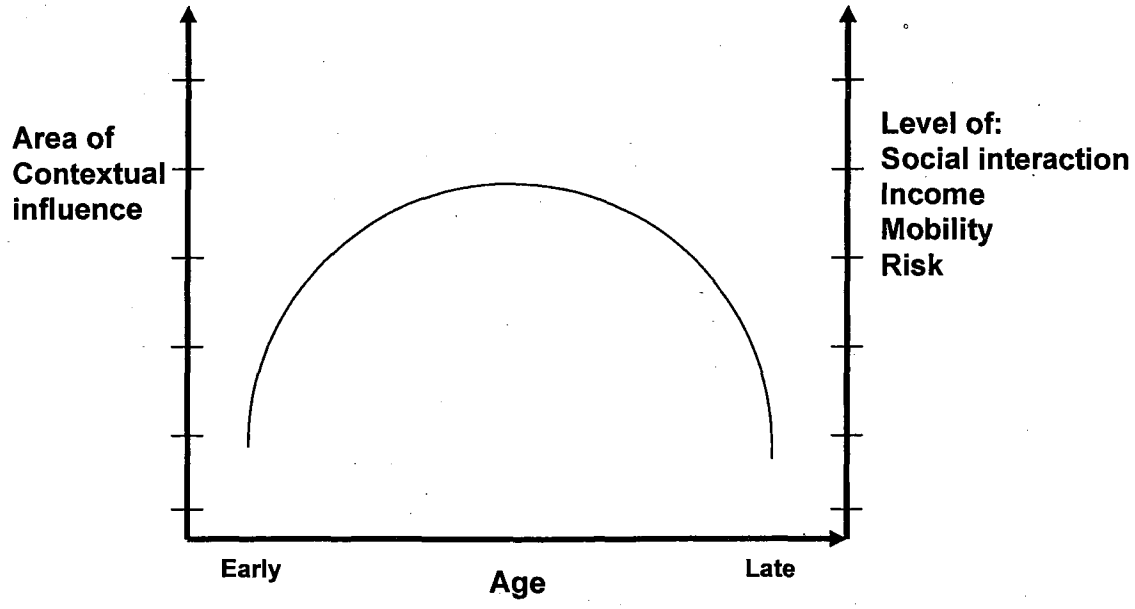

Figure 4.1 *Hypothetical influence of context over the lifecourse.*

Context as a Healthscape

Implementation of a conceptual approach that fuses geographical and social contexts may best be accomplished by adopting a behavioural strategy. Such an approach focuses on the development of empirically validated postulates about individual, group, or mass behaviours that, in turn, inform hypotheses about the spatial structure of context (King, 1969). More formally, the healthscape represents an alternative conceptual approach with which to operationalize context, and is defined as the unique context ascribed to an individual as expressed through the temporal and spatial activities of daily life (Rainham et al., 2008b). The increasing availability of data characterizing individual time-activity patterns, coupled with tools from health geomatics provides an opportunity to explore this approach.

Two central behavioural concepts underlying the healthscape approach are time geography and activity space. Time geography simply represents the spatial and temporal dimensions of all human activities—activities occur in specific places for limited durations (Hägerstrand, 1970). Time and space are integrated in a space-time context where events occur, and certain processes unfold as sequences of situations. Processes are shaped by paths and projects (Pred, 1981). Paths represent a person's movement from one location to another in two-dimensional space. Projects are physical and virtual activities occurring along the path. Algebraically, time geography can be represented by a simple data structure to describe human movement and activities, denoted by x, y, t, a, which define the location (x, y) of activities (a), at specific times (t). These data provide the necessary input for the development of activity spaces.

An activity space is a two-dimensional form[1] or spatial boundary derived from time geographic information that can be used to assess objective spatial structure (Horton and Reynolds, 1971; Newsome et al., 1998). Derivation of the activity space boundary requires input from two elements: movement near place of residence, and movement to and from regular activity locations (such as journeys to work, shopping, or socializing) (Golledge and Stimson, 1997). Objective information about the frequency and mode of participation in activities at specific locations drawn from time geography data is useful in determining the intensity and temporal distribution of activities (Newsome et al., 1998). Activity space concepts have been used in assessing the frequency of health care facility visits by the elderly (Gesler and Meade, 1988), in determining the optimal location of health care facilities (Cromley and Shannon, 1986), and in developing hybrid exposure assessment models in environmental health research (Jerrett et al., 2004).

Figure 4.2 illustrates how the healthscape approach features human behaviour, represented by the activities of people over time, as an important linkage to attributes of context relevant to health. The base of the figure depicts hypothetical boundaries such as census tracts or other administratively-defined geographical units. An indicative space-time path of an individual, starting from home and identifying the locations of activities over the course of a typical day, is overlayed on this display. Above this path is an estimate of the activity space which can be used to extract the components of context hypothesized to be relevant to health.

[1] Activity spaces in larger cities are three dimensional.

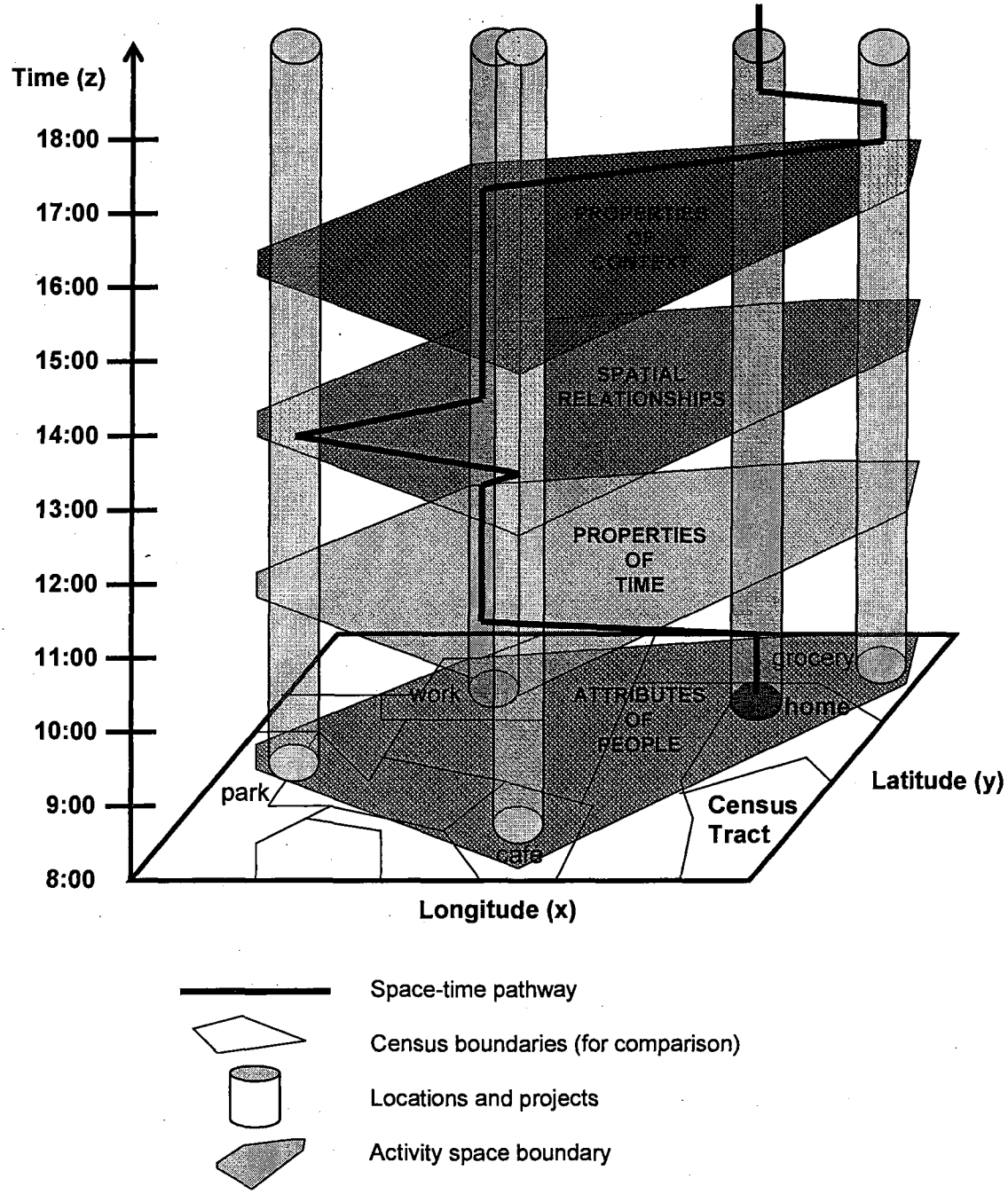

Figure 4.2 *The Healthscape Approach.* The approach integrates theories from time geography and activity space concepts.

This approach has several desirable features. First, it provides an objective way to define context: context is not limited to one area as with conventional approaches, but may include multiple non-adjacent locations. Second, it responds to calls for the integration of human agency into context and health research (CIHI, 2003; Frohlich et al., 2002; Popay et al., 2003). Third, the framework is inherently dynamic. The space-time path can operate on any time scale (minutes to lifetime) which is necessary if the notion of context includes mobility or the importance of context over the lifecourse. Lastly, the bundling of activities produced when two or more space-time paths overlap reveals social space, or the contextual opportunities where social interactions may occur; as samples accumulate a density distribution can be drawn of such paths. Instead of identifying features of context that facilitate sociability from census tract attribute data, it is feasible to identify 'regions' of social interaction and extract features of context from any georeferenced data source.

Constructing the Healthscape

Implementing the healthscapes approach requires specialized data, describing activities and mobility in a spatio-temporal manner, and the geospatial tools capable of handling large amounts of geocoded information. The data to construct space-time paths and activity spaces can be assembled from three sources: time-use surveys, consumption and communication databases, and location aware technologies. Time-use surveys consist of diary-based instruments designed to record time-use and activity patterns using a diurnal scale (Harvey and Pentland, 1999). Several large time-use surveys have also documented supplementary socioeconomic, demographic, and mobility

characteristics of human activity patterns, and are powerful sources of contextual information when linked to health registry or environmental exposure data (Leech et al., 2002). The gold standard for time-use surveys includes data geo-coded for location. For example, a time-use survey conducted in Halifax, Nova Scotia, in 1971, coded the home and activity locations of respondents to locations within a 0.4 km grid (Elliott et al., 1976).

Space-time activity information can also be inferred from communication and consumption data. For example, data from cell phone communications have been used to map and explore the structure of social networks and human mobility patterns (González et al., 2008; Onnela et al., 2007). The dynamics of human mobility over geographic space through time can also be approximated from electronic billing records and associated data streams. Credit and debit card transfers provide details about the time and location of consumption, the nature of the activity (restaurant, gasoline, groceries), as well as descriptions about the products of services purchased. A large amount of useful space-time activity data is collected using internet-based technologies. For example, a recent study analyzed an online database that tracks the movement of $1 (US) bills as an indicator of the spread of infectious disease (Brockmann et al., 2006).

Yet, time-use survey and mobile network approaches provide only partial space-time data required for the construction of the healthscape. Location-aware technologies (LATs) can accurately report or log space-time activity information using radiolocation, radiofrequency identification, or geosensor technologies (Murakami and Wagner, 1999; Stopher et al., 2006). Perhaps the most promising of these technologies are global positioning systems (GPS). Historically, GPS tracking has been used primarily in studies of species range

in wildlife research (Phillips et al., 1998; Rodgers, 2001); more recently, GPS tracking has been employed in the study of human mobility patterns, particularly in conjunction with household travel and time-use surveys (Kwan, 2000; Wolf et al., 2004). Innovations in GPS receiver design have resulted in the development of wearable GPS devices suitable for human tracking over extended periods of time (Rainham et al., 2008a). These devices have been applied in health studies to assess levels of physical activity (Rodriguez et al., 2005; Schutz and Chambaz, 1997; Terrier and Schutz, 2005), to validate time-activity diary data (Phillips et al., 2001), and to improve environmental exposure estimates (Elgethun et al., 2003; Milton and Steed, 2007).

Space-time activity data produce large data sets and presents challenges for analysis. For example, using a GPS receiver to log the space-time locations of an individual at one second intervals over a seven-day period can produce over 600 000 data points. In addition there are several attributes associated with each data point: longitude (x), latitude (y), time (t), date, velocity, and various measures of GPS accuracy. Although it is relatively straightforward to import and visualize GPS data in most GIS software, the conduct of meaningful analysis using standard geographic and statistical routines presents a challenge. These challenges are compounded when space-time data are linked to activity and health outcomes data and the dimensionality of data increases further (Kwan and Lee, 2004; Miller, 2001).

The purpose of collecting vast amounts of GPS or other activity-location data, is to further our understanding of activity space, and to describe with some precision the region in which context is most likely associated with health outcomes. Several studies have used theories and metrics from spatial ecology

to explore the geography of activity spaces (Buliung and Kanaroglou, 2006; Kwan, 1998; Schönfelder et al., 2002). Tools used to measure animal home range are especially useful to the development of the healthscape. Home range is an area defined by the distribution of space-time data within which an animal conducts its normal activities (Burt, 1964; Moorcroft and Lewis, 2006). The objectives of home range analysis are to: (1) measure the spatial extent of all activities over a specified period of time, and (2) assess the spatial intensity of activities (or spatial utilization) within the home range. Ultimately, these home range measures facilitate visualization and quantification of the geographical extent, shape, and dispersion properties of the contexts relevant to health. The spatial unit of analysis for operationalizing and measuring context is determined objectively by the activities of people, rather than by existing (often administrative) spatial units of convenience.

Methods

Based on the preceding discussion, we hypothesize the following:

1. Healthscapes derived from objectively-measured space-time activity data will have morphologies dissimilar to census tracts;
2. healthscape morphology will not be adequately predicted by one or more individual-level health determinants;
3. there is little correspondence between contextual characteristics of the healthscape and the residential census tracts of our sample; and,
4. the healthscapes approach does not explain more variation in one or more health measures than the characteristics of the individual or the residential census tract.

Sampling and Data Processing

The study area is focused on the urban core of Halifax Regional Municipality. Although 76% of the municipal population lives on 4.7% of the land area, the study area is characterized by a mix of urban and suburban development (Statistics Canada, 2006).

Sample recruitment was conducted by a local survey research firm in July 2007. A computer-assisted telephone interviewing system was used to identify one adult (at least 18 yrs of age) from a random sample of households. Sampling was completed once 56 participants had been identified and an equal number of male and female participants were recruited by assigning two operators, each instructed to recruit one participant of either gender. Sample size was limited by financial and time constraints. The crude response rate was 14% (calculated as cooperative contacts / cooperative contacts + refusals). Cooperative contacts were re-contacted by the study team to arrange for deployment of the GPS data loggers and to complete a questionnaire. Three contacts (all male) withdrew from the study resulting in a final sample of 53 participants. Figure 4.3 shows the approximate home locations[2] of participants in the study area.

A member of the research team met with each participant to deploy the GPS data logger and to supervise completion of the questionnaire. The GPS data logger (hereinafter called the "GPS" or "GPS device") is a wearable device specifically designed for the study by the research team described in Chapter 3. It consists of a PVC enclosure containing a 16-channel GPS receiver board, data logger board, and power supply.

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[2] Home locations presented are randomly jittered to within a 1 km radius of the true residential address.

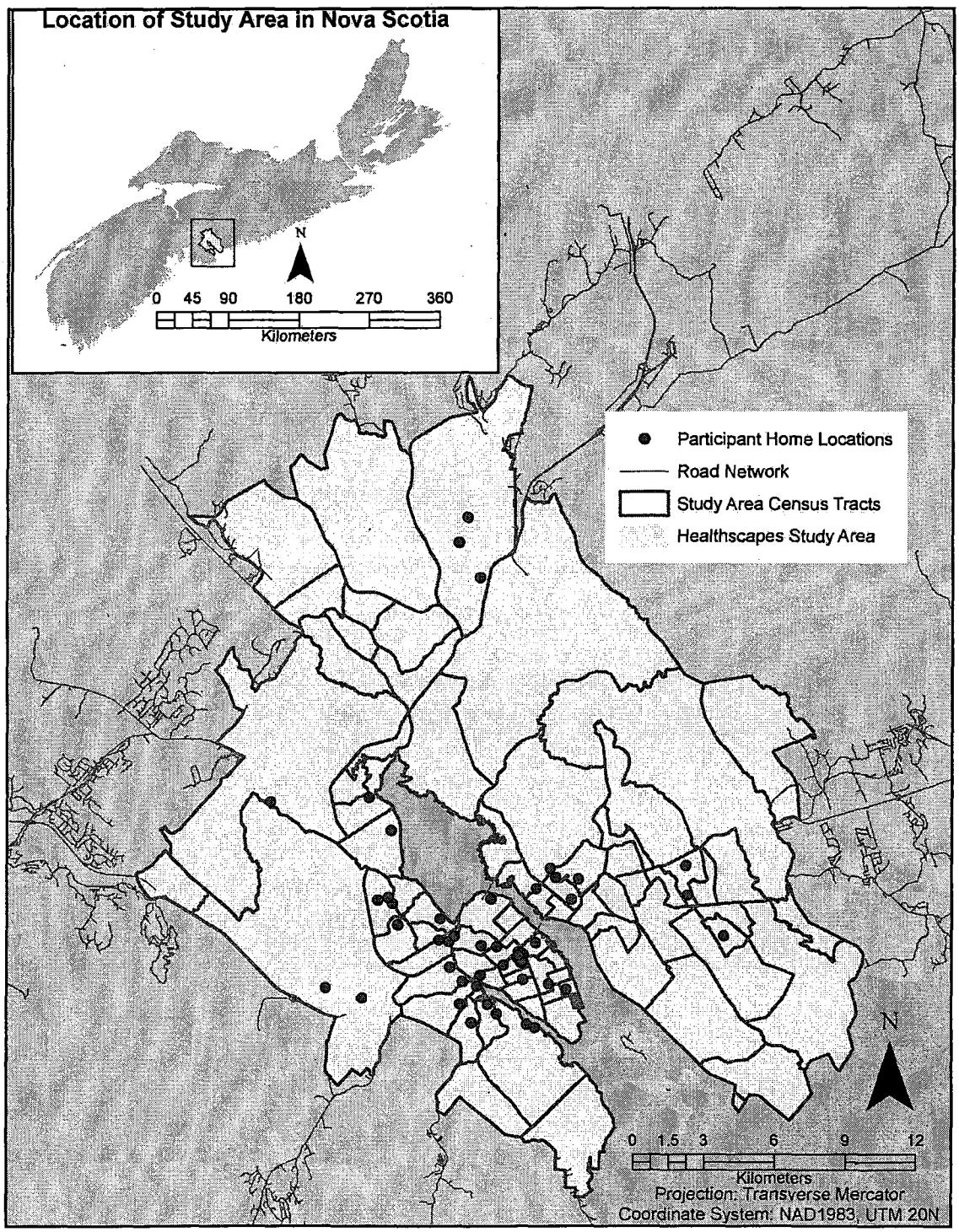

Figure 4.3 *Approximate residential locations of study respondents.* Data were jittered so that locations shown in figure are only accurate to within a 1km radius of true residential location.

The enclosure is worn in a small (7 L) sling pack, with an external antenna originating from the enclosure mounted on the shoulder to maximize exposure to satellite signals. Participants were trained on the use of the device, instructed to charge the battery every evening, and requested to carry the GPS with them at all times unless participating in activities that would jeopardize the integrity of the equipment. All data were logged passively to an SD card. Other than battery maintenance, the GPS requires no further intervention by the participant. Participants were asked to wear the GPS for seven days so that weekday and weekend patterns would be captured.

On retrieval of the GPS, the SD card was removed and the data files were transferred to a computer for processing and analysis. The raw GPS data are stored in NMEA format and require parsing and formatting before further processing can take place. Figure 4.4 shows an illustrative example of 5 seconds of GPS data.

```
$GPRMC,234924.00,A,4439.03948,N,06335.82285,W,0.000,,230707,,,A*63
$GPGGA,234924.00,4439.03948,N,06335.82285,W,1,07,1.27,63.8,M,-23.0,M,,*5C
$GPGSA,A,3,19,08,16,27,25,11,28,,,,,,1.79,1.27,1.27*02
$GPRMC,234925.00,A,4439.03948,N,06335.82285,W,0.000,,230707,,,A*62
$GPGGA,234925.00,4439.03948,N,06335.82285,W,1,07,1.27,63.8,M,-23.0,M,,*5D
$GPGSA,A,3,19,08,16,27,25,11,28,,,,,,1.79,1.27,1.27*02
$GPRMC,234926.00,A,4439.03948,N,06335.82285,W,0.000,,230707,,,A*61
$GPGGA,234926.00,4439.03948,N,06335.82285,W,1,07,1.27,63.8,M,-23.0,M,,*5E
$GPGSA,A,3,19,08,16,27,25,11,28,,,,,,1.79,1.27,1.27*02
$GPRMC,234927.00,A,4439.03948,N,06335.82285,W,0.000,,230707,,,A*60
$GPGGA,234927.00,4439.03948,N,06335.82285,W,1,07,1.27,63.8,M,-23.0,M,,*5F
$GPGSA,A,3,19,08,16,27,25,11,28,,,,,,1.79,1.27,1.27*02
$GPRMC,234928.00,A,4439.03948,N,06335.82285,W,0.000,,230707,,,A*6F
$GPGGA,234928.00,4439.03948,N,06335.82285,W,1,07,1.27,63.8,M,-23.0,M,,*50
$GPGSA,A,3,19,08,16,27,25,11,28,,,,,,1.79,1.27,1.27*02
$GPRMC,234929.00,A,4439.03948,N,06335.82285,W,0.000,,230707,,,A*6E
$GPGGA,234929.00,4439.03948,N,06335.82285,W,1,07,1.27,63.8,M,-23.0,M,,*51
$GPGSA,A,3,19,08,16,27,25,11,28,,,,,,1.79,1.27,1.27*02
```

Figure 4.4 *Raw GPS data output in NMEA format.*

Each sentence begins with the symbol "$" and provides details on the coordinates, time, date, velocity, error, and other data created by the GPS receiver. We developed specialized software to read the raw GPS data files and convert the data into a text file suitable for analysis in a GIS. The software allows users to select specific variables of interest from the NMEA data stream. For the present application, we selected date, time, longitude, latitude, and speed. The software also allows users to specify the measurement units and can handle conversion of the universal coordinated time (UTC) and date stamps into any time zone. Gaps in the data arise when the GPS is turned off for battery charging and when a signal is lost at locations where satellite reception is weak or non-existent. A full data set is required to accurately determine how much time participants spend at specific locations or in transit.

Using the software users can create a 'skeleton' file containing only the beginning and end dates and times within the periods when sampling occurred. The GPS logs data at a frequency of one observation per second; however, the user can specify a different frequency in the skeleton file if fewer observations from the GPS are needed. The newly created skeleton file is then merged with the already processed GPS text file and interactively asks users how gaps in the data should be remedied. There are two options for dealing with missing data. The first is to use the last known position information. This option is suitable when participants have spent time in a single location over a period of time. For example, the lengthiest gaps in the data occur when participants turn off the GPS to recharge the battery at home. The second option is to linearly interpolate locations using the last known and next valid position. This option is more appropriate when signals are lost when participants are mobile. Once

the merge is complete, the user has the option of adding 'derived' variables to the final data set, such as the day-of-the-week derived from the date stamp, distance traveled (calculated using the difference between longitude and latitude coordinates of two locations), and elapsed time (an incremental time value). The final data set is then saved as a comma-delimited text file, formatted for import into any GIS.

A GIS and specialized GIS extensions were required to operationalize the development of individual healthscapes, construct contextual-level variables, and perform spatial operations necessary for the testing of the hypotheses listed previously. Development of individual healthscapes required importing the processed GPS data into the GIS. Each healthscape in this study is represented by the minimum convex polygon (MCP) and kernel density estimate (KDE) calculated from the full GPS data set. As a reminder, the MCP is a shape that completely encloses all GPS data points and measures the maximal geographical extent of an individual's space-time activity data. The area of an MCP is calculated as:

$$Area = \frac{x_1(y_n - y_2) + \sum_{i=2}^{n-1} x_i(y_{i-1} - y_{i+1}) + x_n(y_{n-1} - y_1)}{2}, \qquad (1)$$

where $(x_i, y_i), i = 1,2,...n$, are the coordinates of the locations. The ABODE home range estimation tool[3] was used to calculate the MCP area (km^2) and perimeter (km) for each participant (Laver, 2005). Kernel density estimation provides a two-dimensional surface of the spatial intensity of an individual's activities. The

[3] The code used to generate MCPs in the ADOBE GIS tool was originally developed by Dr. Mike Sawada in the Department of Geography at the University of Ottawa.

result of a KDE is usually a raster dataset where each cell has a density value[4] that is weighted according to the distance from the starting features. The KDE is calculated as:

$$\hat{f}(x) = \left[\frac{1}{(nh^2}\right]\sum_{i=1}^{n} K\left\{\frac{(x - X_i}{h}\right\}, \quad (2)$$

where K is the kernel that determines the shape of the distribution placed over each of the GPS locations, h is the smoothing parameter or bandwidth which controls the search radius or kernel width, and n is the number of GPS points used in the analysis.

The GIS software used for this analysis uses the Epanechnikov kernel, defined as:

$$K = \frac{3}{4}(1 - t^2) \text{ for } t = \frac{d}{h} \leq 1, \text{ and 0 for } t = \frac{d}{h} > 1, \quad (3)$$

where d is the distance between the raster cell and the GPS point, and h is the bandwidth. All KDEs were calculated using an adaptive bandwidth based on a modification of the bivariate normal density that is derived by multiplying the standard deviation of GPS points by a constant as follows:

$$h_{adaptive} = \frac{C\sigma}{\sqrt[6]{n}}, \quad (4)$$

where the constant C = 2.04, σ is the standard deviation term (derived from taking the square root of half of the squared variance estimates of all GPS points in the x and y directions, and n is the sample size. The average bandwidth was 1027.3 m. All estimates were mapped to a raster with a cell size of 20 m. A freely available software extension was used to calculate 95 and 50

[4] KDE values can vary according to the software used. All GIS analysis in this paper was conducted using ESRI ArcGIS 9.2 and the Spatial Analyst extension.

percent volume contours for each KDE[5]. These contours were then converted from lines into polygons so that area and perimeter values could be calculated.

Two contextual variables were also created to facilitate comparison of census tract to healthscape boundaries. The first variable is an index of area-level material deprivation (Pampalon and Raymond, 2000). The following data from the Canadian Census (2006) were abstracted for each census tract: average individual income (15+ years old), unemployment rate (25+ years old), less than high school diploma (25+ years old), proportion of single parents (15+ years old), divorced, separated or widowed (15+ years old), and proportion of people living alone (15+ years old).

Each item was first age-sex standardized using the following formula:

$$\text{Standardized Ratio} = \frac{\sum_i^{12} n_i}{\sum_i^{12} p_i R_i}, \qquad (5)$$

where i indicates age (in one of six groups: 15-24, 25-34, 35-44, 45-54, 55-64, 65+) by sex (male, female) = 12 groups. As an example, we took n to be the number of single parents in the census tract, p the "at risk population" or population size of the age group in the census tract, and R the proportion of single parents in each age group in the province. Z-scores were calculated to standardize values in the six items with different units for principal components analysis (PCA) — a widely used variable reduction method. Two components met the criteria of eigenvalue = 1, and explained close to 70% of the total variance among the six variables. VARIMAX rotation was applied to identify which of the six variables were explained by these two factors. The result

[5] Percent contours were calculated using *Hawth's Analysis Tools* developed by Hawthorne Beyer and downloadable from the website http://www.spatialecology.com.

showed that material deprivation was best explained by average individual income, unemployment rate and less than high school variables. Material deprivation scores were derived from the addition of the standardized variables scores multiplied by their respective weights. The minimum material deprivation score was added to all values to ensure that all values were positive.

The second contextual variable is best conceptualized as a measure social interaction potential. The social dynamics of neighbourhoods are thought to be important for population health and well being. Social interaction potential can be defined as acts of neighbouring or local social interaction (Bridge et al., 2004). A growing body of evidence points to the importance of local social interaction, social cohesion, and sense of community for the promotion of physical and mental health (Kawachi and Berkman, 2003; Parker et al., 2001). Rather than measure social interaction potential directly, we hypothesize that elements of urban design act to encourage or hinder social interaction. Although the evidence in support of social correlates of urban form is mixed, some research has shown that the walkability of neighbourhoods is associated with various aspects of social interaction and connectedness, which can act as mediators between neighbourhood attributes and both physical and mental health outcomes (Du Toit et al., 2007; Frank and Engelke, 2001; Giles-Corti and Donovan, 2002; Wellar, 1996).

An index of social interaction potential for the study area was created using the following indicators: residential dwelling density, land use variety, neighbourhood connectivity, and social land use. The development of these indicators required the spatial integration of cadastral (parcel) data, land use data, and street network data layers in a GIS. The first indicator, dwelling

density, was created by selecting residential land use from the land use data. A centroid was calculated for each residential parcel and a simple density function using a search radius of 100m was employed to create a raster surface of residential density. These data were then normalized to fall in the range 1 to 10. Land use variety was determined by selecting all land use types, except for streets and cells with no data, and was converted into a raster surface using a 10 m resolution. The raster calculator function was used to calculate the variety of land uses around each cell and the data were again normalized so that all values fall between 1 and 10.

Neighbourhood connectivity is based upon the number of unique street connections at each intersection (or the potential for different route choices available at each intersection). Only intersections with 3 or more unique intersecting streets are included in the intersection density calculation. Using the street network layer we calculated the number of streets connecting to each intersection node. Again, a simple density function using a search radius of 100 m was used to create a connectivity surface and all values were normalized to be between 1 and 10. The land use social interaction potential indicator was calculated using the detailed land use descriptions which were compiled in 2007-8 by the Time-Use Research Program at St. Mary's University (Spinney, 2008). The file provides detailed information on the type of activities that take place within the larger land use categories. We also created a binary variable of land use social interaction potential. Land use activities that may encourage social interaction were given a value of 10 and all other uses a value of 0. Land use activities with a score of 10 included: bowling/billiard/arcade, churches, campgrounds, concert halls, theatres, movie houses, gold courses, hotels,

libraries, mixed uses, municipal parks and open spaces, taverns/night clubs/bars, non-profit organizations, recreation and sport clubs/complexes/arenas, restaurants, retail grocery and convenience stores, and retail plazas/malls. These land use activity data were joined based on spatial location to the land use layer polygon and converted to raster surface with a 10 m resolution.

The final index of social interaction potential is calculated using the four indicators derived above. The scores (each ranging from 1 to 10) for each indicator (dwelling density, land use variety, neighbourhood connectivity, and land use social interaction potential) are summed for each grid cell resulting in a possible index score of 4 to 40.

Each participant also completed a questionnaire containing a range of questions designed to capture socio-demographic information, health status and behaviours, and perceptions of neighbourhood quality. Copies of the letter of information and consent, and the questionnaire appear in appendices 4 and 5. The survey, approximately 30-40 min in length, was completed under supervision of a research team member so that any questions about the survey instrument could be responded to immediately. Responses to selected survey questions are presented in Table 4.1. There were no missing responses among the variables of interest.

A substantive portion of the questionnaire asked respondents to rate their health status using the SF-36 measurement model (Ware, Jr. et al., 1994). The model consists of eight scales: physical functioning, limitations in physical and emotional health, bodily pain, general health, vitality, social functioning, and mental health.

Table 4.1
Characteristics of the survey sample and contextual-level variables

Survey Question/variable		
Derived item: age	Mean (*n*)	48.4 (53)
Derived item: respondent's gender	Female (%, *n*)	49.1 (26)
What is the highest level of education you have completed?	Some high school (%, *n*)	5.7 (3)
	Completed high school	3.8 (2)
	Trade certificate or vocational training	7.5 (4)
	Diploma or certificate from college	18.9 (10)
	Some university	18.9 (10)
	University degree	24.5 (13)
	Post-graduate education	20.8 (11)
What was your approximate household income from all sources in 2007?	< $16,000 (%, *n*)	7.5 (4)
	16-29,999	11.3 (6)
	30-39,999	9.4 (5)
	40-49,999	9.4 (5)
	50-59,999	17.0 (9)
	60-69,999	13.2 (7)
	≥ $70,000	32.1 (17)
What is your current employment situation?	Employed, full time (%, *n*)	56.6 (30)
	Employed, part time	15.1 (8)
	Unemployed	13.2 (7)
	Homemaker	5.7 (3)
	Student, full time	3.8 (2)
	Other (specify)	5.7 (3)
Do you smoke tobacco (cigarettes or cigars)?	Yes (%, *n*)	17.0 (9)
What activities do you participate in during an average month? (Indicate duration in hours per month)	All exercise (mean, *n*)	38.5 (49)
	Walking	23.7 (49)
	Hiking	4.3 (13)
	Jogging or running	10.6 (10)
	Swimming	3.9 (10)
	Exercise equipment	12.2 (17)
	Aerobics	12.0 (2)
	Organized sports	8.1 (8)
	Other?	17.6 (18)
Calculated summary measure: Physical health (SF-36)	Transformed T value (mean, sd)	51.1 (9.6)
Calculated summary measure: Mental health (SF-36)	Transformed T value (mean, sd)	50.8 (7.8)
In general, would you say your health is:	Excellent (%, *n*)	22.6 (12)
	Very good	45.3 (24)
	Good	22.6 (12)
	Fair	5.7 (3)
	Poor	3.8 (2)
Calculated index: neighbourhood quality /100	Mean (sd)	70.4 (13.5)
Context/variable		
Census Tract	Material deprivation score (mean, sd)	2.1 (0.9)
	Social interaction score (mean, sd)	6.8 (2.2)
Minimum convex polygon	Material deprivation score (mean, sd)	2.3 (0.4)
	Social interaction (mean, sd)	6.3 (1.4)
Kernel density estimate (95%)	Material deprivation score (mean, sd)	2.1 (0.5)
	Social interaction (mean, sd)	7.2 (1.3)
Kernel density estimate (50%)	Material deprivation score (mean, sd)	2.1 (0.7)
	Social interaction (mean, sd)	7.2 (2.1)

Linear transformations were performed on the scores from each scale to produce summary measures of physical and mental health. Self-rated health status was measured using a five-point Likert scale with the following options: excellent, very good, good, fair, or poor health.

Although self-rated health status is a component of the physical summary measure, it was extracted from the summary measure and used in the analysis so that the results would be directly comparable to other studies that typically use the item as a primary measure of health status. To measure health behaviours, questions were asked about smoking and frequency of physical exercise. Socio-demographic data on age, gender, education, household income, and employment status were also collected.

The notion that perception of neighbourhood quality could be related to health status is suggested by conceptual and empirical research indicating that characteristics of the physical environment, social status, and the neighbourhood environment are independently related to health differences (Macintyre et al., 2002; Wilson et al., 2004). An index of neighbourhood quality was developed based on 9 items (Cronbach's alpha = 0.77). The items used to measure NQI were compiled from several sources (Dunn, 2002; Ellaway & Macintyre, 2004; ESRC, 2002).

Analytical Stages

The morphology and utility of healthscapes as spatial units for evaluating the effects of context on health were addressed according to the following sequence of analytic stages:

Stage 1. *Do individuals with residence in the same census tract generate similar healthscape morphology?*

To address this question we compared the morphology (area, perimeter, compactness and fractal index) of the minimum convex polygon and kernel density estimate of individuals to the morphology of their residential census tract, limiting the analysis to those individuals who live in the same census tract. Area and perimeter of the healthscapes were calculated and added to the attribute table for each polygon. The compactness of each shape was measured using a circularity ratio (*CR*), expressed mathematically as:

$$CR = \frac{4\pi(area)}{perimeter^2}. \quad (6)$$

The geometric complexity of each healthscape was measured by calculating its fractal dimension (Olsen et al., 1993). This measure is commonly used to describe irregular and fragmented patterns in nature. In medicine, for example, the morphology of tissue samples used in histopathology is commonly assessed using fractal dimension measures (Cross and Cotton, 1992). The fractal dimension (*D*) for individual healthscapes was calculated using the equation:

$$D = \frac{2\left(\ln\left(\frac{perimeter}{4}\right)\right)}{\ln(area)}, \quad (7)$$

If the census tract is truly an appropriate spatial unit to delineate the context relevant to health, then all individuals in the same census tract should hypothetically exhibit similar activity patterns and healthscape boundaries. Two tests were performed to evaluate the similarity of activity patterns and healthscape boundaries. A one-sample Wilcoxon Signed Rank Test was employed to compare the morphology of the minimum convex polygons and

kernel density estimate polygons to the residential census tract. We then examined whether the morphology of the polygons were similar across the sub-sample by measuring the dispersion of the distribution of morphology values using the coefficient of variation statistic.

Stage 2. *Are the number of census tracts traversed and the geographical extent of the healthscape associated with an individual's health status or socio-demographic characteristics?*

The purpose of this analysis is to investigate whether the extent of an individual's activities is a function of health status, behaviours or socio-demographic characteristics. An association would imply that insight into the geographical extent of context might be explained partially by characteristics of the individual. To explore these associations, Spearman's rank correlation coefficient ρ, a non-parametric measure of association, was used when both variables were expressed in the form of ratios. Kendall's tau was used to estimate correlations between ratio and ordinal variables (education, income and self-reported health status). Point biserial correlation was employed to estimate associations between ratio and binary (or dichotomous) variables (gender, employment, smoking status).

Stage 3. *Are the characteristics of the census tracts covered by the geographical extent of an individual's healthscape comparable to the individual's residential census tract?*

The residential census tract is the most commonly used spatial unit in research on context and health. If compositional and contextual measures derived from the census tract unit are statistically significantly correlated to the measures derived from the healthscape, then the residential census tract may

suffice as an appropriate unit for analysis. Two contextual measures, material deprivation and a sociability index, were calculated for each participant's residential census tract, minimum convex polygon, and kernel density estimate polygons (95% and 50% spatial intensity polygons). The level of association between the census tract and healthscape values for both indices were estimated using Spearman's ρ.

Stage 4. *How do contextual measures at the census tract and healthscape levels compare when employed to explain variations in health status after accounting for the influence of individual-level health determinants?*

Multivariate hierarchical models were employed to examine the relationships between physical and mental health outcomes, individual-level survey and socio-demographic variables, and measures of material deprivation and sociability at the census tract and healthscape levels. Hierarchical regression here should not be confused with multilevel analysis, a statistical approach that explicitly investigates the interaction between individual and group level characteristics, usually in the form of a hierarchy with nested data structures (Hox, 2002). Hierarchical regression is a form of multiple linear regression in which terms are added to the model in stages or blocks and changes in model fit are evaluated statistically (Mueller et al., 1977). Variables were entered in a block fashion to see how model fit and the prediction of variance changed across models. Five regression models were developed. The first involved modeling the effects of the strongest individual-level predictors on health. The next four models added contextual-level variables derived from census tract or healthscape geographies. Model fit, variance change and other regression statistics were used to compare the contextual measures from

census tract and healthscape levels. The Durbin-Watson statistic was used to test for the independence of model residuals.

A similar analytical process using binary logistic regression models was employed for self-rated health status as the dependent variable. Self-rated health status was dichotomized into excellent+very good+good and fair+poor categories to facilitate analysis. Socio-demographic data were also dichotomized, including education (college/higher education or less than college), household income (≥ $60,000 or < $60,000), employment (employed or unemployed), smoking status (non-smoker or smoker), and exercise (> 36 hours/month or ≤ 36 hours/month). Cut points for income and exercise represented the point where a superimposed Lowess curve changed direction for self-rated health on scatterplots. Model fit and predictive value were assessed using the Hosmer and Lemeshow goodness-of-fit test, model chi-square, and Nagelkerke's R^2. Multilevel modeling was not used as it has stringent sample data requirements (Paterson and Goldstein, 1992; Singer and Willett, 2003).

Results

Table 4.2 provides a number of descriptive statistics relating to the temporal and spatial characteristics of the GPS data at the participant level. A total of 9,554 hours (398 days) of location data were collected of which approximately 79% are on weekdays. The average participant logged 180.3 hours of data (7.5 days), and close to 65% of these hours was spent at home. A little more than 70% of the time was spent within the residential census tract; on average, participants traversed 26 distinct census tracts as part of their

weekly activities. Bolded values represent the results from eleven participants from the same census tract and do not differ significantly from other values. The majority of participants reside on the peninsula or in the most urbanized areas of Halifax. Almost 23% of the participants live in suburban areas.

A collection of healthscapes was constructed for each participant. Figure 5A and figure 5B show the minimum convex polygon and kernel density estimate polygons (KDE95 and KDE50), respectively, for one participant derived from seven days of GPS data. The convex polygon gives an indication of the complete spatial extent of all participant activities that, in general, encompass a large area since it includes all locations of activities as well as all locations associated with travel among them.

The KDE polygons in Figure 5B represent the spatial intensity of activities across geographical space. The KDE50 circle (dark grey) captures 50% of these activities and distinguishes contexts within a relatively short distance from residential location. The KDE95 polygons capture 95% of all activities and effectively represent an individual's activity space(s).

The MCP and KDE geographies are unique for every individual. Moreover, the KDE polygons will always be nested within the MCP since it represents the complete spatial home range of an individual, while the KDE geographies represent the spatial intensity of activities within the home range.

Table 4.2
Participant GPS Data Characteristics and Location Information

ID	Logged Total (Hours)	Days	Logged SA[a] (Hours)	Logged SA Weekdays (Hours)	Logged SA Weekend (Hours)	Time at Home (Hours)	Time Inside CT[b] (Hours)	Time Outside CT (Hours)	Time Outside CT in SA (Hours)	Total CTs Covered in SA	Total CTs Covered
1[c]	**193.1**	**8.0**	**143.10**	**135.50**	**7.6**	**93.1**	**96.7**	**96.4**	**46.5**	**47**	**53**
2	118.2	4.9	118.20	70.20	48.0	101.2	102.7	15.5	15.5	10	10
3	77.7	3.2	77.70	29.70	48.0	70.0	70.7	7.0	7.0	4	4
4	166.9	7.0	166.90	118.90	48.0	109.5	110.5	56.4	56.4	20	20
5	166.4	6.9	166.40	118.40	48.0	113.1	114.9	51.5	51.5	22	22
6	166.1	6.9	96.70	96.70	0.0	60.4	63.0	103.1	96.7	43	44
7	260.3	10.8	260.30	164.30	96.0	166.5	167.6	92.7	92.7	25	25
8	61.2	2.6	58.40	58.40	0.0	51.0	55.8	5.4	2.6	19	21
9	167.7	7.0	167.70	119.70	48.0	26.1	26.6	141.1	141.1	25	25
10	152.2	6.3	89.40	89.40	0.0	55.4	57.8	94.4	31.6	21	24
11	168.0	7.0	159.20	111.20	48.0	133.1	153.0	15.0	6.2	39	43
12	243.6	9.8	236.10	153.20	82.9	218.9	220.3	23.3	15.8	37	38
13	86.7	3.6	86.70	58.50	28.2	28.3	77.6	9.1	9.1	6	6
14	188.4	7.8	188.40	141.10	47.3	138.7	154.8	33.6	33.6	6	6
15	147.1	6.1	120.60	82.60	38.0	68.2	69.4	77.7	51.2	32	33
16	163.8	8.8	159.90	115.80	44.1	98.3	108.8	55.0	51.1	26	28
17	204.0	8.5	200.50	87.10	113.4	180.9	185.6	18.4	14.9	16	16
18	43.8	1.8	43.80	43.80	0.0	14.0	14.5	29.3	29.3	12	12
19	131.0	5.5	131.00	83.90	47.1	72.2	73.1	57.9	57.9	16	16
20	183.1	7.6	157.70	135.10	22.6	109.6	111.8	71.3	45.9	34	35
21	212.5	8.9	165.40	109.30	56.1	87.1	92.2	120.3	73.2	56	57
22	178.4	7.4	148.10	105.80	42.3	95.5	106.7	71.7	41.4	31	33
23	21.5	0.9	21.50	0.00	0.0	12.9	12.9	8.6	8.6	11	11
24	185.0	7.7	185.00	137.00	48.0	107.1	109.5	75.5	75.5	26	26
25	170.9	7.1	170.90	122.90	48.0	164.7	167.9	3.0	3.0	10	10
26	168.8	7.0	168.80	120.80	48.0	152.5	161.9	6.9	6.9	15	15
27	424.0	17.7	420.10	280.00	140.1	346.9	355.4	68.6	64.7	35	36
28	287.8	12.0	275.70	197.00	78.7	166.0	169.8	118.0	105.9	44	45
29	156.7	6.5	138.50	96.30	42.2	131.0	131.9	24.8	6.6	29	31
30	162.4	6.8	162.40	114.40	48.0	126.8	140.5	21.9	21.9	5	5
31	169.5	7.1	169.50	121.50	48.0	155.6	163.4	6.1	6.1	23	23
32	182.9	7.6	169.00	126.00	43.0	117.9	128.9	54.0	40.1	26	30
33	162.4	6.8	150.40	114.50	35.9	105.6	107.4	55.0	43.0	35	35

Table 4.2 (Cont'd)

ID	Logged Total (Hours)	Days	Logged SA[a] (Hours)	Logged SA Weekdays (Hours)	Logged SA Weekend (Hours)	Time at Home (Hours)	Time Inside CT[b] (Hours)	Time Outside CT (Hours)	Time Outside CT in SA (Hours)	Total CTs Covered in SA	Total CTs Covered
34	288.1	12.0	215.20	167.40	47.8	116.8	142.5	145.6	72.7	42	45
35	**161.2**	**6.7**	**157.80**	**113.10**	**44.7**	**133.9**	**139.0**	**22.2**	**18.8**	**48**	**51**
36	80.9	3.4	74.90	57.50	17.4	55.4	57.7	23.2	17.2	39	41
37	211.1	8.8	202.10	160.40	41.7	138.2	190.0	21.1	12.1	17	19
38	164.5	6.9	164.50	116.50	48.0	110.0	117.7	46.8	46.8	22	22
39	195.6	8.2	195.60	147.60	48.0	114.7	118.3	77.3	77.3	45	45
40	260.2	10.8	166.20	81.45	84.7	205.4	221.9	38.3	38.3	37	38
41	396.3	16.5	181.70	122.60	59.1	154.2	168.9	227.4	12.8	24	25
42	156.4	6.5	136.80	96.50	40.3	116.6	126.9	29.5	9.9	42	44
43	201.3	8.4	193.10	145.20	47.9	114.8	177.3	24.0	15.8	18	18
44	**173.4**	**7.2**	**173.40**	**125.40**	**48.0**	**142.1**	**154.8**	**18.6**	**18.6**	**11**	**11**
45	**230.3**	**9.6**	**223.40**	**151.40**	**72.0**	**146.6**	**148.0**	**82.3**	**75.4**	**15**	**15**
46	**267.0**	**11.1**	**265.10**	**214.80**	**50.3**	**118.5**	**173.8**	**93.2**	**91.3**	**31**	**32**
47	**48.1**	**2.0**	**47.80**	**47.80**	**0.0**	**36.8**	**37.7**	**10.4**	**10.1**	**16**	**17**
48	**167.9**	**7.0**	**167.90**	**143.90**	**24.0**	**142.6**	**153.9**	**14.0**	**14.0**	**9**	**9**
49	**163.8**	**6.8**	**167.90**	**126.50**	**37.3**	**78.7**	**84.2**	**79.6**	**79.6**	**37**	**37**
50	**204.5**	**8.5**	**204.50**	**156.50**	**48.0**	**140.5**	**142.3**	**62.2**	**62.2**	**15**	**15**
51	211.4	8.8	211.40	115.40	96.0	148.7	156.4	55.0	55.0	18	18
52	**218.7**	**9.1**	**214.33**	**143.40**	**70.9**	**169.2**	**185.3**	**33.4**	**29.0**	**21**	**23**
53	**181.7**	**7.6**	**172.20**	**127.40**	**44.8**	**103.2**	**118.9**	**62.8**	**53.3**	**43**	**44**
Mean (SD[d])	180.3 (73.3)	7.5 (3.1)	164.3 (65.0)	117.4 (45.8)	46.5 (27.9)	116.3 (56.3)	126.4 (59.0)	53.9 (44.2)	40.8 (31.7)	25.6 (13.0)	26.5 (13.8)
Same CT Mean (SD[d])	**182.7 (55.2)**	**7.6 (2.3)**	**176.1 (55.2)**	**135.1 (39.4)**	**40.7 (22.7)**	**118.7 (37.9)**	**130.4 (43.1)**	**52.3 (33.3)**	**45.4 (29.1)**	**26.6 (14.9)**	**27.9 (16.3)**

[a] SA = Study area geography
[b] CT = Census tract geography
[c] Bolded values indicate participants with residence in the same census tract
[d] Standard deviation

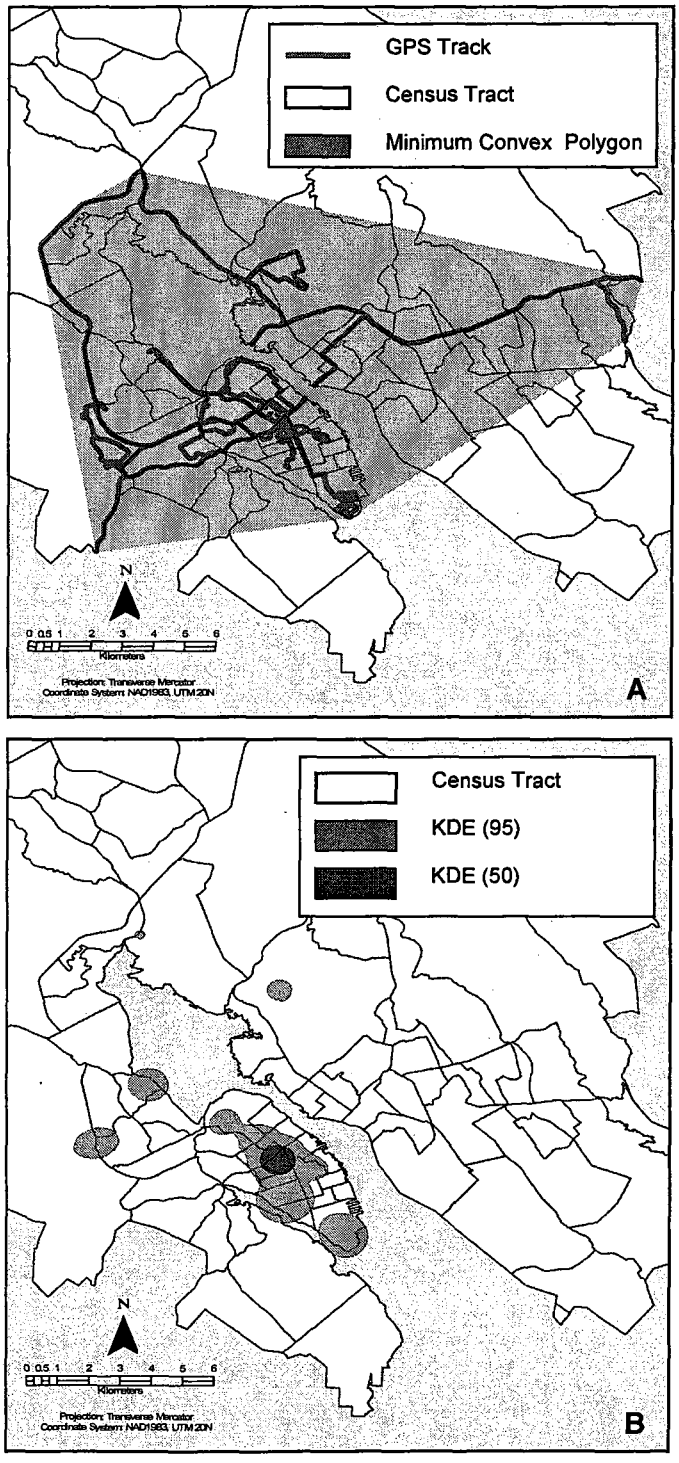

Figure 4.5 *Representations of the healthscape resulting from an individual's seven-day GPS track.* (A) shows the respondent's spatial home range, (B) shows the spatial intensity of the respondent's activities with 95% of activities located in the grey-shaded areas (KDE95); 50% of al activities are located in the darker circle (KDE50) which is centered on place of residence

The healthscapes represented by MCPs and KDEs are potentially quite useful as an approach to investigate the influence of context on health. First, the healthscapes show that the influence of contextual phenomena to health is more geographically diffuse than is typically reported in studies using census tracts. Context does not necessarily have to be limited to a single area or spatial unit. For example, the results of a spatial query found that a respondent's KDE95 and KDE50 polygons contained the centroids of 12.5 and 3.3 census tracts, respectively. These empirical results suggest that context is more accurately comprised of multiple census tracts. Moreover, the number of influential census tracts is positively associated with the proximity of an individual's residence to its census tract boundary.

While the MCP provides an estimate of an individual's spatial home range, it gives no indication of what contexts within the range are more or less associated with health. The KDE polygons, on the other hand, represent the spatial intensity of activities in geographical space and thus accurately feature contexts more likely to be relevant to health. Figure 4.6 shows the KDE95 and KDE50 polygons from one respondent for a seven-day period. By linking the GPS coordinates with a civic address file in a GIS, it is possible to determine the types of activities each respondent engaged in over the study period.

The results clarify that the use of census tracts in place and health studies will result in misclassification (geographically and numerically) of the contexts relevant to health.

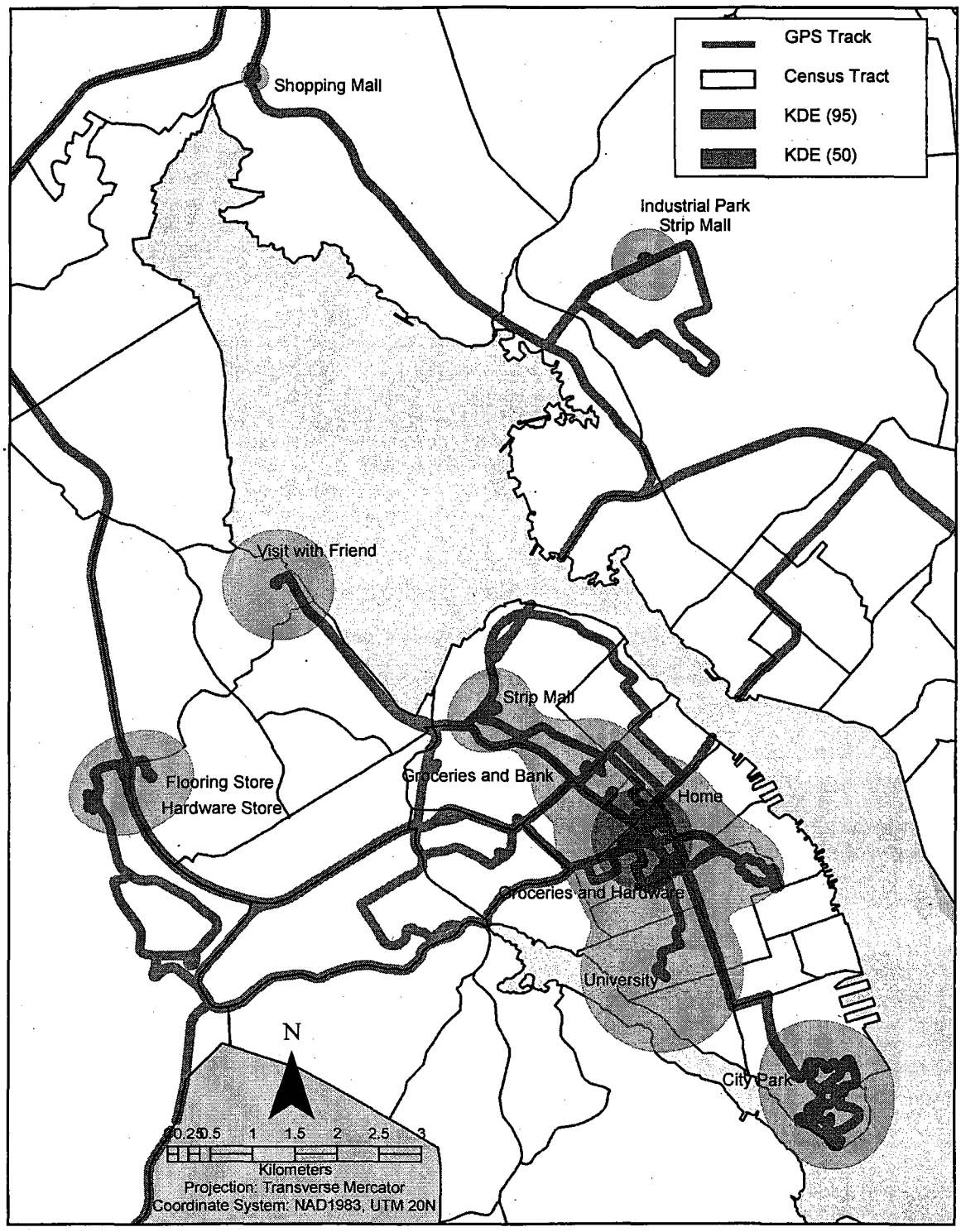

Figure 4.6 *Seven-day healthscape of one respondent.* The 50% kernel density estimate (KDE) represents an area of GPS locations clustered around their residence. The 95% KDE polygons represent well the spatial context(s) where activities occur. Note that a person may have more than one "health-influencing" context. Use of the residential census tract to represent context underestimates these important influences.

Table 4.3
Analytical Stage 1: Summary characteristics and assessment of the similarity of healthscape morphology from respondents living in the same census tract (N=11)

	Min.	Mean	Max.	Median (estimated)	Wilcoxon Statistic	p^a	CV[b]
Area (km²)							
MCP[c]	2.70	91.10	260.90	83.49	66.0	0.004	106
KDE (95)[d]	2.98	7.04	17.36	5.88	66.0	0.004	65
KDE (50)[e]	0.75	1.08	1.95	0.96	48.0	0.041	36
Perimeter (km)							
MCP	6.96	34.64	64.03	34.70	66.0	0.004	65
KDE (95)	6.15	14.75	38.40	10.67	66.0	0.004	72
KDE (50)	3.07	3.95	7.38	3.48	21.0	0.307	34
Compactness							
MCP	0.36	0.68	0.80	0.70	51.0	0.120	19
KDE (95)	0.15	0.59	0.99	0.60	29.0	0.756	49
KDE (50)	0.45	0.92	1.00	0.99	64.0	0.007	20
Fractal Dimension							
MCP	0.99	1.01	1.04	1.00	14.0	0.100	1
KDE (95)	0.98	1.02	1.10	1.02	37.0	0.756	4
KDE (50)	0.98	0.99	1.04	0.98	2.0	0.007	2

[a] p-values
[b] CV: coefficient of variation (%)
[c] MCP: minimum convex polygon
[d] KDE (95): kernel density estimate polygon (95% of all respondent locations)
[e] KDE (50): kernel density estimate polygon (50% of all respondent locations)

In light of this finding it would seem prudent to explore the variability of healthscapes among the participants to investigate whether health outcomes or socio-demographic status are related to various measures of the healthscape, and to compare the performance of census tracts and healthscapes in modeling the association between context and health. The remainder of this section is focused on the results of the four analytical stages in sequence, beginning with healthscape analysis of individuals from the same census tract.

Healthscape Morphology: Participants with Residence in Same Census Tract

Wilcoxon tests were used to compare the morphology of the residential census tract of a subsample of eleven participants to their healthscapes, represented by minimum convex polygons and kernel density estimate polygons (Table 4.3). The coefficient of variation was also calculated to provide an indication of the distributional variability among the healthscapes for each morphology measure. Overall, the minimum convex polygon displays the most variation in morphology, likely due to fact that it reflects that absolute differences in the total number of GPS locations between participants. As a measure of the intensity of activity locations, the kernel density estimate polygons are usually smaller in area and more compact.

Generally the median areas and perimeters of the healthscapes are significantly different than those of the residential census tracts; however, this difference is especially evident when the KDE95 is used, capturing 95% of all locations. Even when this level of detail is reduced to the KDE50, capturing 50% of all locations, the census tract is significantly different in area. Indeed, the areas and length of the perimeters of the KDE50 polygons was not significantly different than the perimeter of the residential census tract. Wilcoxon values for measures of compactness and fractal dimension indicate that MCP and KDE95 polygons are similar to residential census tract values; the reverse is true, however, for KDE50 polygons which are significantly dissimilar to the residential census tract.

In practical terms, the area and perimeter measures are more indicative of the differences between census tract and healthscape morphology. For the most part, the area of the residential census tract gives a poor representation of

the true area that may influence health. The data suggest that census tract areas do not even represent 50% of the respondent locations measured in this study. The compactness and fractal dimensions exhibited greater similarity between the census tract and healthscape measures. The process behind the creation of the census tract boundary is completely unrelated to the development of the healthscapes. In Halifax, the majority of census tract boundaries follow road networks.

In summary, values of the coefficient of variation across measures of healthscape morphology indicate the existence of extensive variability among participants from the same census tract. Variations among participants are greatest for MCPs, an estimate of their spatial home range, followed by KDE95 polygons. While there are no set numerical criteria against which the coefficient of variation is to be interpreted, the results provide a reasonably good argument against the use of a single residential census tract to represent the contexts to which an individual is exposed. Although the morphology of census tracts and healthscapes may be quite dissimilar, it might not be necessary to resort to healthscapes if it were proven to be feasible to predict a person's healthscape from knowledge of their socio-demographic status. The following section explores this possibility.

Healthscapes, Health and Socio-demographic Status

Relationships between healthscape measures, health and socio-demographic status are shown in Table 4.4. In addition to the geographical representations of the healthscape (MCP and KDE polygons), three additional healthscape characteristics were included for analysis. The residential to other

census tract ratio is a ratio of the number of hours spent inside the residential census tract to the number of hours spent in other census tracts. Values below one are indicative of a more compact healthscape. The two additional characteristics include the number of hours spent outside the residential census tract (half of the ratio above), and the total number of census tracts traversed as measured by the GPS location data. The area of the MCP and KDE polygons was used in the analysis. As there are no studies with which to compare these results, the table includes values significant at the $p \leq 0.10$ level to identify additional variables with moderate influence.

Several socio-demographic variables were related to healthscape measures. Age was significantly and negatively related to the ratio of time in and out of the residential census tract ($\rho = -0.354$, $p = 0.011$), the time spent outside the residential census tract ($\rho = -0.452$, $p = 0.001$), the area of the KDE50 polygons ($\rho = -0.464$, $p = 0.001$), and less significantly related to the area of the KDE95 polygon ($\rho = -0.262$, $p = 0.079$). This finding is corresponds to the ideas presented in Figure 4.1, that the geographical extent of context(s) relevant to health vary with position in the lifecourse, and become narrower with age. Without data from individuals under 18 years of age, it is difficult to determine whether the sign of the association between age and healthscape measures is positive or negative. It appears that contexts outside the residential census tract are more likely to be influential as mobility increases and obligations to work become more stable. These preliminary associations are supported by the significantly positive relationships between employment status and healthscape measures. Employed participants spent more time

outside their residential census tract (r_{pb} = 0.370, p = 0.007), and had larger KDE50 (r_{pb} = 0.290, p = 0.035) polygon areas.

Table 4.4
Analytical Stage 2: Significant[a] correlations between healthscape measures and socio-demographic and health variables (N=53)

Healthscape Measure	Variable[b] ($p \leq 0.05$)	Variable[b] ($p \leq 0.10$)
Residential to Other Census Tract Ratio[c]	Age: -0.354, p = 0.011 Physical health: 0.326, p = 0.019	
Time Outside Residential Census Tract	Age: -0.452, p = 0.001 Employment: 0.370, p = 0.007 Physical health: 0.356, p = 0.010	
Total Census Tracts Traversed	Smoking: 0.320, p = 0.018	
Minimum Convex Polygon	Smoking: 0.310, p = 0.024	Household Income: 0.159, p = 0.087
Kernel Density Estimate (95)[d]		Age: -0.262, p = 0.059 Employment: -0.240, p = 0.079
Kernel Density Estimate (50)[e]	Age: -0.464, p = 0.001 Employment: 0.290, p = 0.035 Physical health: 0.356, p = 0.010	Mental health: -0.238, p = 0.087

[a] Bonferroni correction for multiple comparisons would adjust significance level to $p \leq 0.006$
[b] Health and socio-demographic variables tested include: age, gender, employment, education, household income, amount of exercise, smoking, physical and mental health (SF-36 summary measures), and self-reported health status
[c] Ratio = total time spent within residential census tract / time spent elsewhere
[d] KDE (95): kernel density estimate polygon containing 95% of all respondent locations
[e] KDE (50): kernel density estimate polygon containing 50% of all respondent locations

Physical health and health behaviours were also associated with certain healthscape measures. The ratio of time in and out of the residential census tract (ρ = 0.326, p = 0.019), time spent outside the residential census tract (ρ = 0.356, p = 0.010), and the KDE50 polygon (ρ = 0.356, p = 0.010) are significantly and positively related to physical health status. Interestingly, it

seems that the ability to access locations outside one's immediate neighbourhood is beneficial to health status. While the healthscape measures provide some indication of the scale of contextual influences, they do not give any information about the types of resources that support health. The issue of appropriate spatial scale for analysis of context and health has been noted by several studies (Macintyre et al., 2002; Mitchell et al., 2000). A somewhat surprising finding is the significant relationships between smoking and the total number of census tracts traversed ($r_{pb} = 0.320$, $p = 0.018$) and the area of an individual's home range ($r_{pb} = 0.310$, $p = 0.024$). This preliminary finding suggests that smokers have a much larger spatial home range than non-smokers. Seven out of the nine smokers in the study sample live in suburban neighbourhoods suggesting that more travel would be required to acquire resources.

In summary, there is evidence to suggest that the geographical extent, and thus the influence of contexts outside of the residential census tract is associated with socio-demographic characteristics and physical health status. This finding has several implications. First, conventional context and health studies may underestimate the variability of contexts relevant to health; this bias will likely diminish the importance of context as it relates to health. Second, studies of context and health should, if unprepared to collect detailed time-space activity data, adjust for the larger geographical influence of context as it is associated with the age, employment, mobility, and health status of the population under study. The scale of analysis may play a role in mediating or possibly confounding context and health relationships. The prevalent use of census tracts in exploring context and health relationships only serves to

amplify the uncertainties of the influence of scale. Although the results presented here do not imply a causal relationship, the associations between healthscape measures, health and socio-demographic characteristics suggest that the contexts important to health should not be limited to census tract geography.

Material Deprivation and Social Interaction Potential

In this analytical stage, a correlation analysis was undertaken to ascertain whether contextual measures of material deprivation and social interaction potential measured at the census tract level were related to the same measures using healthscape geographies (Table 4.5). Material deprivation at the census tract level was significantly and positively related to deprivation measured at the KDE95 healthscape level ($\rho = 0.628$, $p = 0.000$) and KDE50 level ($\rho = 0.908$, $p = 0.000$). The relationship with material deprivation at the MCP level was not significant. The index of social interaction potential measured at the census tract level was significantly and positively associated with social interaction potential measured in the MCP ($\rho = 0.488$, $p = 0.000$), KDE95 ($\rho = 0.798$, $p = 0.000$) and KDE50 ($\rho = 0.850$, $p = 0.000$) healthscape geographies. The strength of the association increased as the area of the healthscape decreased.

Table 4.5
Analytical Stage 3: Relationships between contextual variables measured at the healthscape and census tract levels; Spearman's ρ (N=53)

Healthscape Measure	Material Deprivation	Sociability Index
Minimum Convex Polygon	-0.058, p = 0.674	**0.488, p = 0.000**
Kernel Density Estimate (95)[c]	**0.628, p = 0.000**	**0.798, p = 0.000**
Kernel Density Estimate (50)[d]	**0.908, p = 0.000**	**0.850, p = 0.000**

[c] KDE (95): kernel density estimate polygon containing 95% of all respondent locations
[d] KDE (50): kernel density estimate polygon containing 50% of all respondent locations

Calculation of the coefficient of determination provides insight into how much material deprivation or social interaction potential at the healthscape level can be predicted by the variation of the same variable at the census tract level. For material deprivation the data suggest that about 39% and 82% of the proportion in variation within the KDE95 and KDE50 polygons respectively can be predicted by measures of material deprivation at the census tract level. The lower correlation for KDE95 indicates the lower predictive adequacy of the census tract indicator of context. Correlations of social interaction potential were significant across all three healthscape measures and social interaction potential measured at the census tract level can predict anywhere from 24% to 72% of the variation in social interaction potential among the healthscape geographies.

These results are illuminating for two reasons. First, the KDE95 polygon provides a reasonably accurate depiction of the intensity of an individual's activities in geographical space because it is based on objectively measured

data from the GPS devices. Since the correlation coefficients for material deprivation and sociability for the KDE95 healthscape were 39% and 63% respectively, we can state with some confidence that the use of census tracts in conventional context and health research may underestimate the actual influence of these, and possibly other variables when estimating their impact on health.

Second, contrasts in the predictive variability of sociability at the census tract level to the much larger geography of the MCP, and the more local geography of the KDE50 polygon, give an indication how issues of scale may influence the results of quantitative modeling approaches.

It has been acknowledged elsewhere that researchers should be more considerate of the scale(s) at which it is theorized that context influences health (Curtis and Jones, 1998; Macintyre et al., 2002; Tunstall et al., 2004). For example, while the KDE50 and census tract correlation of material deprivation is quite strong, the KDE50 polygon represents only half of the activity intensity of an individual within its boundaries. The results presented here provide support for the notion that researchers should devote more effort toward the study of how the influence of contextual data varies with different scales. Using GPS or other space-time activity information will benefit researchers concerned with identifying bias associated with misclassifying contextual influences of health.

Healthscapes and Census Tracts: A Comparison

Regression models were run to compare the contribution of contextual variables (material deprivation and the index of social interaction potential)

measured at census tract and healthscape geographies in explaining the distribution of health among the study participants. The first regression models (Model 1 = empty model) included individual-level socio-demographic predictors of health. These predictors were selected using a forward stepwise approach with the condition that the predictors were statistically significant ($p \leq 0.05$). A single contextual variable from either the census tract or healthscape geographies was added to each subsequent model and the results were compared using measures of model fit. The focus of this approach is on the differences in the contribution of the variables to the model using unique levels of geography, rather than on the value and direction of the regression coefficients. The contribution of the contextual variable is measured as the difference in the adjusted R^2 values between the empty model (always Model 1) and each subsequent regression model.

Tables 4.6 and 4.7 provide the results of multivariate hierarchical regression modeling of physical health, a summary measure of health derived from the SF-36 questionnaire. The first models in both tables include only individual-level predictors of age and household income, which explain about 27% of the variability in physical health. In Table 4.6, models 2 to 5 show the results from the inclusion of material deprivation as a contextual-level predictor of physical health using census tract and healthscape geographies. The addition of material deprivation measured at the census tract (Model 2), MCP (Model 3) and KDE50 (Model 5) geographies resulted in a decrease of R^2 values of between 0.5 to 1.5%. However, material deprivation measured at the KDE95 level increased the predictive ability of the model by 2.6%.

Table 4.6
Multivariate hierarchical regression models; estimating the contribution of contextual-level material deprivation index to variations in physical health: comparison of census tracts to healthscape measures

	Model 1			Model 2			Model 3			Model 4			Model 5		
	B	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*
Age	-0.29	0.07	-0.48****	-0.29	0.07	-0.48****	-0.29	0.08	-0.48****	-0.31	0.07	-0.51****	-0.26	0.07	-0.49****
Income	1.30	0.56	0.28**	1.30	0.57	0.28**	1.31	0.58	0.28**	1.10	0.56	0.24*	1.20	0.57	0.26**
Census Tract				0.01	1.22	0.00									
Minimum Convex Polygon							0.60	3.00	0.03						
Kernel Density Estimate (95)										-4.18	2.47	-0.20*			
Kernel Density Estimate (50)													-1.33	1.56	-0.10
Durbin-Watson			1.917			1.917			1.913			2.001			1.918
Constant	59.06	4.46		59.05	4.46		57.45	9.27		69.36	7.49		62.35	5.92	
R^2_{adj}			0.271			0.256			0.256			0.297			0.266
R^2_{diff}[a]			0.000			-0.015			-0.015			0.026			-0.005
F			10.65****			6.96****			6.97****			8.32****			7.29****

Significance: *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, **** $p < 0.001$
[a] Model 1 R^2 = reference

Table 4.7
Multivariate hierarchical regression models; estimating the contribution of a contextual-level index of social interaction potential to variations in physical health: comparison of census tracts to healthscape measures

	Model 1			Model 2			Model 3			Model 4			Model 5		
	B	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*
Age	-0.29	0.07	-0.48****	-0.29	0.08	-0.47****	-0.30	0.07	-0.49****	-0.29	0.08	-0.47****	-0.29	0.08	-0.48****
Income	1.30	0.56	0.28**	1.32	0.57	0.28**	1.29	0.57	0.27**	1.30	0.56	0.28**	1.30	0.56	0.28**
Census Tract				0.20	0.55	0.05									
Minimum Convex Polygon							-0.14	0.85	-0.02						
Kernel Density Estimate (95)										0.35	0.91	0.05			
Kernel Density Estimate (50)													0.11	0.57	0.02
Durbin-Watson			1.917			1.911			1.924			1.923			1.916
Constant	59.06	4.46		57.21	6.71		60.02	7.46		56.13	8.78		58.05	6.84	
R^2_{adj}			0.271			0.258			0.256			0.258			0.256
R^2_{adj}*			0.000			-0.013			-0.015			-0.013			-0.015
F			10.65****			7.02****			6.97****			7.03****			6.97****

Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, **** $p < 0.001$
[a] Model 1 R^2 = reference

Table 4.7 shows the results of regression models run to examine the effects of social interaction potential on physical health after controlling for individual-level predictors. Again, the first model was run without including sociability as a contextual variable. Inclusion of social interaction potential at the census tract level and healthscape geographies did not improve the ability of the model to predict variations in physical health.

Tables 4.8 and 4.9 show the regression results of models predicting variation in a summary measure of mental health, also derived from the SF-36 questionnaire. The strongest individual-level predictors as represented in the first model of both tables were household income and self-reported assessment of neighbourhood quality (R^2_{adj} = 13.6%). Table 4.8 shows the decrease in R^2 after the inclusion of material deprivation for census tract and healthscape geographies. Although the addition of material deprivation at the contextual level did not make a contribution to explaining additional variance in mental health, the smallest R^2 change was detected for the KDE95 geography. Interestingly, the sign of the regression coefficients was negative for census tract and MCP geographies, but positive for the KDE95 and KDE50 geographies. In the latter case an increase in material deprivation is associated with a non-significant improvement in mental health status. In Table 4.9, the addition of a contextual measure of social interaction potential at the census tract and both KDE geographies resulted in a decrease in R^2 of between 0.9 and 1.3% when compared to the reference R^2 in Model 1. However, social interaction potential measured at the level of the minimum convex polygon contributed an additional 0.8% to the R^2. Although not statistically significant, higher values of social interaction potential were associated with an improvement in mental health.

Table 4.8
Multivariate hierarchical regression models; estimating the contribution of a contextual-level material deprivation index to variations in mental health: comparison of census tracts to healthscape measures

	Model 1			Model 2			Model 3			Model 4			Model 5		
	B	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*
Income	0.93	0.51	0.24*	0.92	0.52	0.24*	0.92	0.51	0.24*	0.97	0.52	0.25*	0.95	0.52	0.25*
Neighbourhood Quality	0.16	0.08	0.28**	0.16	0.08	0.27*	0.15	0.08	0.27*	0.18	0.08	0.31**	0.17	0.08	0.29**
Census Tract				-0.09	1.12	-0.01									
Minimum Convex Polygon							-0.74	2.70	-0.04						
Kernel Density Estimate (95)										1.68	2.37	0.10			
Kernel Density Estimate (50)													0.52	1.46	0.05
Durbin-Watson			1.996			1.998			1.993			1.987			1.970
Constant	35.02	5.45		35.37	6.87		37.25	9.78		29.87	9.11		33.23	7.48	
R^2_{adj}			0.136			0.118			0.120			0.127			0.120
R^2_{adj}[a]			0.000			-0.018			-0.016			-0.009			-0.016
F			5.09***			3.33**			3.36**			3.52**			3.37**

Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, **** $p < 0.001$
[a] Model 1 R^2 = reference

Table 4.9
Multivariate hierarchical regression models; estimating the contribution of a contextual-level index of social interaction potential to variations in mental health: comparison of census tracts to healthscape measures

	Model 1			Model 2			Model 3			Model 4			Model 5		
	B	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*
Income	0.93	0.51	0.24*	0.95	0.52	0.25*	0.99	0.51	0.26*	0.94	0.51	0.25*	0.93	0.51	0.24*
Neighbourhood Quality	0.16	0.08	0.28**	0.16	0.08	0.28**	0.15	0.08	0.27**	0.16	0.08	0.28**	0.17	0.08	0.29**
Census Tract				0.24	0.47	0.07									
Minimum Convex Polygon							0.90	0.74	0.16						
Kernel Density Estimate (95)										0.53	0.77	0.09			
Kernel Density Estimate (50)													0.27	0.49	0.07
Durbin-Watson			1.996			1.987			2.001			1.960			1.970
Constant	35.02	5.45		33.24	5.52		29.44	7.08		30.92	8.06		32.56	7.17	
R^2_{adj}			0.136			0.123			0.144			0.127			0.123
R^2_{adj}[a]			0.000			-0.013			0.008			-0.009			-0.013
F			5.09***			3.43**			3.93**			3.52**			3.44**

Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, **** $p < 0.001$
[a] Model 1 R^2 = reference

Five binary logistic regression models were run for each of the contextual measures of material deprivation and the index of social interaction potential in order to examine the effects of independent predictor variables on good+very good+excellent (positive) self-rated health status. In the first model in both tables (modeling the effect of the individual-level predictors), household income was the strongest predictor of positive self-reported health status (OR = 25.689, 95% CI 1.751-376.860), followed by age (OR = 0.908, 95% CI 0.830-0.993).

Table 4.10 reveals the results of subsequent models run to assess the contribution of material deprivation to explaining good/very good/excellent self-reported health status at the contextual level, represented by the census tract and healthscape geographies. In Models 2 and 3, the contribution of material deprivation measured at the census tract and MCP geographies respectively did not contribute to improvements in predicting positive self-reported health status. However, contribution of material deprivation at the KDE95 and KDE50 geographies accounts for an extra 2.5% and 1.4% of the variance in positive self-reported health status respectively.

Table 4.11 reports the results of logistic regression models using the index of social interaction potential as the contextual-level contribution to predicting positive health status. Models 2 and 3 show increases in the model R^2 of 3.0% and 3.9% when compared to the reference model, after the inclusion of social interaction potential at the census tract and MCP geographies. The contribution of social interaction potential at the KDE95 and KDE50 geographies did not explain any additional variance in the odds of participants reporting positive self-reported health status. All of the regression models demonstrated a good fit to the data according to goodness-of-fit tests.

Table 4.10
Logistic regression models; probability of good, very good or excellent self-rated health status using contextual measures of material deprivation: comparison of census tracts to healthscape measures

	Model 1			Model 2			Model 3			Model 4			Model 5		
	B	*SE B*	Exp(*B*)	*B*	*SE B*	Exp(*B*)	*B*	*SE B*	Exp(*B*)	*B*	*SE B*	Exp(*B*)	*B*	*SE B*	Exp(*B*)
Age	-0.10	0.05	0.91**	-0.10	0.05	0.91**	-0.10	0.05	0.91**	-0.11	0.05	0.90**	-0.11	0.05	0.90**
Income	3.25	1.37	25.69**	3.26	1.39	26.14**	3.27	1.39	26.32**	3.13	1.41	22.95**	3.31	1.41	27.50**
Census Tract				-0.05	0.58	0.96									
Minimum Convex Polygon							0.19	1.49	1.20						
Kernel Density Estimate (95)										-1.10	1.26	0.33			
Kernel Density Estimate (50)													-0.50	0.76	0.61
Constant	6.06	2.64	430.99**	6.25	3.51	516.42*	5.59	4.65	268.07	9.13	4.72	9193.54*	7.72	3.78	2241.40**
Percent Correctly Classified			92.5			92.5			90.6			90.6			90.6
Hosmer & Lemeshow			2.18 (0.975)			2.79 (0.947)			2.73 (0.950)			8.19 (0.415)			7.80 (0.453)
Model χ^2			13.21***			13.21***			13.22***			14.03***			13.67***
Nagelkerke R^2			0.475			0.475			0.475			0.500			0.489
R^2_{adj}[a]			0.000			0.000			0.000			0.025			0.014

Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, **** $p < 0.001$
[a] Model 1 R^2 = reference

Table 4.11
Logistic regression models; probability of good, very good or excellent self-rated health status with contextual measures of social interaction potential: comparison of census tracts with healthscape measures

	Model 1			Model 2			Model 3			Model 4			Model 5		
	B	*SE B*	Exp(*B*)	*B*	*SE B*	Exp(*B*)	*B*	*SE B*	Exp(*B*)	*B*	*SE B*	Exp(*B*)	*B*	*SE B*	Exp(*B*)
Age	-0.10	0.05	0.91**	-0.12	0.06	0.88**	-0.12	0.06	0.89**	-0.10	0.05	0.91**	-0.10	0.05	0.91**
Income	3.25	1.37	25.69**	3.45	1.46	31.47**	3.84	1.58	46.52**	3.26	1.38	26.02**	3.35	1.50	26.62**
Census Tract				-0.39	0.42	0.68									
Minimum Convex Polygon							-0.72	0.51	0.49						
Kernel Density Estimate (95)										0.06	0.53	1.06			
Kernel Density Estimate (50)													0.08	0.38	1.09
Constant	6.06	2.64	430.99**	10.30	5.69	29735.04*	12.03	5.62	167868.90**	5.61	5.07	272.63	5.37	4.10	215.65
Percent Correctly Classified			92.5			94.3			94.3			92.5			92.5
Hosmer & Lemeshow			2.18 (0.975)			1.13 (0.997)			1.48 (0.993)			2.83 (0.944)			1.20 (0.997)
Model χ^2			13.21***			14.17***			15.46***			13.22***			13.25***
Nagelkerke R^2			0.475			0.505			0.544			0.475			0.476
R^2_{diff}[a]			0.000			0.030			0.039			0.000			0.001

Significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, **** $p < 0.001$
[a] Model 1 R^2 = reference

Discussion

With respect to the research questions, we found that participants with residence in the same census tract do not generate similar healthscapes based on the space-time activity information derived from the GPS devices. Statistical analysis comparing the healthscape morphology to the census tract, and examination of the within sample variability, suggests that a significant portion of time is spent outside of the residential census tract. In addition, the individuals we surveyed exhibited space-time activity patterns varying considerably in area and character. Census tracts do not capture many activities or locations relevant to individual weekly routine activities.

As an alternative to predefined administrative boundaries, we investigated the potential utility of a healthscapes approach to bounding context for place and health research. Bivariate and multiple regression models were employed to evaluate whether the healthscapes generated from the GPS data are related to individual-level health or socio-demographic measures. A few trends emerged.

First, the size of a person's healthscape (or the amount of context they are exposed to) decreases with as age increases. Although we only have results for persons over 18 years old, the data support our hypothesis of the existence of an inverted U-shaped relationship between age and the area of contextual influence. This result has implications for context and health research employing longitudinal designs or utilizing a lifecourse approach to analysis.

Second, employment status (employed or unemployed) was also associated with some of the healthscape measures. For example, employed

participants spend more time outside of their residential census tract, and have a much larger 'home' neighbourhood (KDE50) than unemployed participants.

In addition to age and employment status, participants who reported being healthy according to the physical measures summary spent more time outside their residential census tract and had larger KDE50 healthscapes than less physically healthy participants. The ability to access resources in other contexts external to the residential census tract appears to be beneficial to physical health. With objective information about the location of a person's space-time activity patterns it is possible (as was shown in Figure 4.6) to identify the resources that may enhance or diminish the conditions for health. The significant but weak relationship between smoking status and home range is of some interest. Participants who reported being smokers traversed a large number of census tracts and had significantly-larger MCPs than non-smokers. Further analysis revealed that a majority of these individual's lived in suburban neighbourhoods meaning they would have to travel further distances for employment and to acquire the resources necessary for health.

The degree of correlation between variables measured at the census tract level and those at the level of the healthscape is pertinent since it gives a crude indication of the performance of census tracts in estimating the contribution of context to health. Since the healthscapes are derived from objectively-measured space-time activity information, they provide a reasonably accurate indication of the actual context relevant for health research. Mean values of material deprivation and sociability were similar for census tracts and healthscapes. Material deprivation at the census tract level was strongly and significantly correlated with the KDE50 polygons, moderately correlated with the KDE95

polygons, and unrelated to material deprivation measured at the minimum convex polygon level. The index of social interaction potential at the census tract level was positively correlated with all of the healthscape geographies, strongly correlated with the KDE50 polygons, and moderately correlated with the KDE95 and minimum convex polygons. The lower association between the census tract and KDE95 values for material deprivation and social interaction potential speaks to the relative advantage of the healthscapes approach and its potential for operationalizing context in place and health studies.

Calculation of the coefficient of determination indicates that the census tract predicts approximately 82% and 40% of the variation in material deprivation at the KDE50 and KDE95 geographies respectively. Similarly, the census tract predicts approximately 72%, 64%, and 24% of the variation in sociability at the KDE50, KDE95, and MCP geographies. If we consider the healthscape geographies to be a more accurate representation of context, and that it would be prudent to include the majority of space-time activity locations in modeling an individual's spatial context, then the results show that use of census tract geography may underestimate by half, or more, the true variation in contextual-level measures. It would be misleading to award equivalent contextual scores to everyone living in a given census tract.

The most common modeling scenario in context and health research is to measure how much of the variation in a specific health outcome is related to measures of context after controlling for the influence of individual-level variables. Regression analysis provides an opportunity to evaluate the relative contribution of contextual variables measured at the census tract and healthscape geographies after controlling for individual-level predictors. The

greatest improvement in explaining the variability in physical health resulted from the addition of material deprivation measure at the KDE95 geography. However, the results were less clear for models with sociability as a contextual influence, regardless of the health outcome chosen. While far from being definitive, there is some evidence that contextual-level variables measured at the KDE95 level can explain additional variance beyond that explained by an individual's personal socio-demographic status and the contextual information derived from their census tract. Possessing more detailed information about an individual's space-time activities may provide a more accurate estimate of the variation in the health outcome under study. The results, however, are the product of models with a very small sample size, and warrant confirmation using a larger, more definitive data set.

Conclusion

This chapter combines theories from spatial ecology and tools from health geomatics to develop a form of geography called the healthscape, suitable for context and health research. We also evaluated the healthscape in reference to the census tract which is the conventional geography used in context and health studies. The goal was to advance methods for evaluating the influence of contextual exposures and processes on health.

Time-location data were collected from small random sample of individuals using a novel wearable GPS data logging device, and processed into a series of unique spatial units that defined the spatial extent as well as the intensity of their activities over an average seven-day period. This approach overcomes some of the conceptual and logistical challenges faced by

conventional studies of context and health, including a reliance on static representations of context by a residential address. Our findings indicate that an average of approximately 30% of additional contextual influence (as defined by geographic area) could be overlooked in studies using predefined administrative geographies. In addition, contextual measures of material deprivation and social interaction potential at the census tract level could only predict 40 to 60% of the variation in these measures at the healthscape level using the KDE95 polygon which represents the spatial intensity of 95% of all participant activities. Although few studies have actually quantified the amount of bias in studies using administrative boundaries, our study confirms the findings of several other empirical studies that census tracts do not capture contexts relevant to individual or family activities (Chaix et al., 2005; Kwan & Lee, 2004). In another study it was found that more than 90% of geo-coded activities for 35 families were outside the census tracts of residence (Matthews et al., 2005). While there are good arguments for using census tract, or other administrative geographies, studies should at the very minimum justify their use and speculate as to how bias associated with misclassification of context could affect the results.

We found that the spatial extent of an individual's healthscape is related to health and socio-demographic characteristics, especially with physical health, age, employment status and household income, although the relationships were moderate to weak. The relationship between age and healthscape has been explicated in work looking at neighbourhood ties across the lifecourse (Diez Roux, 2001). Our data show that middle-aged, employed, high income earners report being healthier (physically) than others in our sample; they have

significantly larger healthscapes, and thus experience a greater variety of contexts. We speculate that developing an enhanced perspective on how these or other individual characteristics are associated with context will lead to more refined empirical studies of the relation between context and health.

We found a contextual effect on health that persisted after controlling for several socio-demographic characteristics of the respondents, especially for physical health and self-reported health variables. Although not statistically significant, the contribution of contextual measures at the healthscapes level to explaining additional variance in health, in particular for the KDE95 geography, was greater than the contribution from the same measures at the census tract level. In short, our analytical question pertaining to the ability of context measured using healthscape geographies to explain more variance beyond that explained by individual-level characteristics was supported by the data. However, the lack of statistical significance could be attributable to either: 1) the small sample size of the study; or, 2) other characteristics of context that would be more suitable for explaining variations in individual health outcomes. Moreover, the averaging of values comprising the index of sociability within the larger healthscape geographies could minimize the importance of contextual variation within the healthscape.

An important and related issue has to do with how context is defined. Although a majority of an individual's activities may occur outside their residential census tract, they may only account for a short period of time or may be benign from a health perspective. Several authors have attempted to develop frameworks of context built on the concept of accessibility to resources required to support and improve health (Curtis & Jones, 1998; Macintyre et al.,

2002; Sastry et al., 2002). A benefit of the healthscapes approach is the ability to objectively assess which resources are important and when resources are accessed. This information is particularly useful in the development of policies to improve the salutogenic properties of places.

The use of individual space-time activity information to operationalize context and define spatial units of analysis fundamentally differs from studies where contextual space is defined by mapping individual perceptions of neighbourhood boundaries (Coulton et al., 2001; Ellaway et al., 2001) or is defined according to historical/traditional precedence (Ross et al., 2004). Operationalizing context according to objectively measured information does not limit researchers to define the boundaries of context according to the health outcome or contextual influences of interest. For example, several studies have designed zones based on the spatial distribution of a variety of socio-economic indicators, or on the distribution of indicators predicted to be associated with the health outcome of interest (Cockings and Martin, 2005; Haynes et al., 2007). The methods used to develop healthscape geographies add to the growing literature on alternative approaches to conceptualize and define the contexts thought to be associated with health.

There are several advantages to having access to individual space-time activity data for context and health research. First, the data provide a complete picture of the spatial (which to some extent allow for inference about activities) and temporal patterns of individuals. This is especially useful, for example, for epidemiological investigations of environment and health relationships where the time spent in a location can be used as a proxy for exposure. Researchers interested in social space and disease diffusion could align the data in a

temporal fashion across the study sample and investigate the characteristics of shared contexts. For example, planners and active living researchers may be interested to know more about individual mobility patterns and the locations of high caloric expenditures. Second, the data can be generated in combination with technologies that measure physiological or exposure information. For example, the GPS device used to collect individual space-time activity data in this study could be linked to a heart-rate monitor or air quality sensor (Elgethun et al., 2003; Milton & Steed, 2007; Pandian et al., 2007). These data would provide novel insights into how contexts are also associated with objectively-measured health status and exposure data.

While the healthscapes approach provides a potential powerful tool with which to investigate context and health, there are also several critical issues deserving attention. One concern is that each healthscape is unique to the individual from whom the GPS or time-activity data were derived. It also means that researchers will have to spend more time preparing the data for processing. While census data and its associated geographies are readily available, the preparation of contextual level information for healthscapes relies on spatial extraction methods. These include the identification of intersecting geographies, data that fall completely within the healthscape (or the centroid of a polygon that fits within the healthscape), or the splitting of data into proportions determined by the distribution of another variable.

In this study we used intersecting geographies and centroids that fall within to extract census tract data for the development of the material deprivation measure. However, the choice of the reference geography as well as

the choice of extraction technique can dramatically influence the resulting contextual estimates for the spatial area of interest (Schlossberg, 2003).

Another issue is the influence of adjacent contexts to the healthscape, or those contexts that are physically distant to the healthscape of interest. Here, it was possible to operationalize context as a representation of an individual's spatial footprint over the course of a week. However, the analysis proceeded, as it does with most context and health research, without regard to the context(s) adjacent to the healthscape that might be influencing the characteristics of the healthscape, or the health and socio-demographic characteristics of the study population. Moreover, the context within the healthscape is the result of a two-way dynamic between the characteristics of the area and the modifications of that area resulting from the activities of people who live there.

Finally, there is very little guidance on the appropriateness of using metrics from spatial ecology for the development of healthscape geographies. For example, the minimum convex polygon represents the spatial home range of an individual over a specific time period. However, the MCP is sensitive to the amount of location data collected. Individuals with longer sampling periods are more likely to have larger MCP areas. We limited the analysis to within a specified geographic boundary so that unusual locations, such as those arising from holidays or extraordinary trips are not included in the development of the healthscape. Using the kernel density estimation approach reduces the area imbalances created because of sampling time since it measures the spatial intensity of activities in space. However, even KDE approaches are not efficient at representing a more realistic notion of context that acknowledges the importance of physical or social networks and mobility. For example, the

scheduling of an array of important activities will vary from person to person, and will vary according to their ability to organize time, to travel among contexts, and to secure the resources necessary for health.

Broadening approaches to studying the relationships between context and health will require a more complete understanding of context as defined through a set of locations physically connected to the social spaces experienced during the course of daily life. This work represents an initial exploration of a novel approach to operationalizing context for health research. Most studies of this type are limited to a single contextual geography – the census tract. We utilized measures of individuals' space-time activity patterns to form an objective representation of context. Although the collection of high resolution time-location data is not feasible for every study, there is no reason why future studies of context and health cannot take into account, even in a small way, a more accurate account of locations where activities occur that may or may not be associated with health. The preliminary empirical results suggest that a healthscapes approach to identifying and operationalizing context has considerable potential to contribute to studies of the relationships between context and health.

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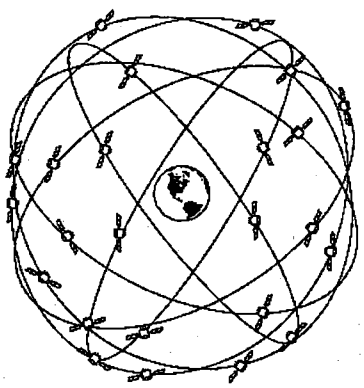
Chapter 5

Integrated Discussion



Introduction

This thesis makes a number of technological and analytical contributions both to population health research and health geography. Specifically, it integrates theory and technology to explain, in concrete terms, how contextual features of society can manifest in individual heath outcomes. This chapter of the dissertation provides an integrated discussion of the study findings as they relate to the conceptualization of the healthscape, the ecology of context, and future research opportunities.

The dissertation takes as its starting point an interest in the differential distribution of health status that is associated with the attributes of 'place', as well as the characteristics of individuals. The past two decades have witnessed an emerging consensus that the determinants of health are geographically patterned. This emerging consensus has been subsumed under what is known as a place-based perspective. In this view, characteristics of context that follow from the composition of the population, the attributes of the area of interest, or influences from contexts external to the study area or population of interest are believed to influence health and health-related behaviour.

Put differently, there is evidence of an intimate connection between health experiences and outcomes and the geographical and social settings within which they unfold (Gould and Wallace, 1994). This is identified in the dissertation as only a partial explanation, however, that contains a number of critical silences and gaps. In short, what is missing is a more concretized concept of context that is theoretically unambiguous, and that is operationalized empirically as a spatial form more reflective of human dynamics.

The effort to fill this gap identified a number of important theoretical developments.

Contributions to Conceptualizing Context

The Healthscapes Approach

As a study in the field of health geography, this dissertation contributes to the sub-discipline of place-based health research through conceptual and methodological innovations in the modeling of contextual elements involved in the spatial patterning of health. A review of the field revealed relatively little past research on the potential usefulness of time-geography for health research, despite the identification of physical and social environmental factors as key features of the population health approach. This is not to say that advances have not been made in the discovery of contextual features relevant to health. Rather the focus of health geography and population health has been on the functional elements of context; this has detracted from a more comprehensive perspective that includes insight into how people position themselves in a variety of contexts at specific points in time (Batty et al., 2003). This thesis complements and builds on the few efforts to implement a more relational approach to context and health research.

Chapter 2 of the dissertation proposes a *healthscapes* approach as an integrative framework for investigating contextual influences of health status, drawing on theories from spatial ecology that first emerged in the 1950s, and from the sub-discipline of time-geography articulated in the early 1970s. These elements contribute to both health geography and population health by: 1) advancing the structural-agency debate by focusing on how place and people

interact with and influence each other, and 2) exploring the scale of the contexts in which place and health relationships might be identified. A healthscapes approach focuses on the ways in which the contextual elements of society manifest in the concrete, day-to-day lives of people and their activities in specific places over time, producing patterns of geographical differences in health status. In short, the healthscape comprises the spatial, temporal and contextual terrains that influence health status.

Measuring the Ecology of Social Structure

If examined through a time-geographical lens, the population health perspective suggests that patterns in health status (with geographical differences used as the basis for identifying health inequalities) result from a fundamental dialectic between individual and society: the interplay between individual agency, the interactions among people as well as the functional and structural relationships occurring between people and context. While 'context' is theoretically cloudy and difficult to operationalize empirically, the structuring of space is inseparable from social structuring processes; that is, the social becomes the spatial and the spatial becomes the social. These theoretical notions are hypothesized to drive explanation of relationships between context and health, and the role of individual agency in the operationalizing context.

Hägerstrand (1985) suggests that three dimensions of human agency – capabilities, convergence, and authority – are crucial components shaping the activities of individuals, and give emphasis to the significance of power relationships in the structuring of context. The ability of individuals to pursue any activity is influenced by physical and social conditions, genetic

predisposition, or the latitude to acquire and control resources for personal gain. These activities may coincide in space and time with other people, tools or resources, leading to variations in levels of social interaction or support. However, human agency can be restricted territorially by forces asserting influence and control over geographic areas. The culmination of these dimensions leads to the structuring of context and invariably the processes leading to the social structuring of society (Parkes and Thrift, 1980; Pred, 1983). These are themes common to both population health research and health geography, and the use of Hägerstrand's time-geographic concept has excellent potential for contributing to an improved explanation of how context influences health status; this thesis adopts a time-geographic approach to investigate how human agency is translated into activities with spatial and temporal properties, which essentially help to identify the contexts relevant to health.

A means by which reciprocal relationships between agency and the structure of context are reproduced is by the social networks of individuals. Core to social networks is the analysis of structural or relational data derived from the patterning of social entities such as people, groups, or organizations (Berkman, 2000; Wasserman and Faust, 1994; Wellman and Berkowitz, 1997). On this view, social structures arise from networks and are partially responsible for determining individual behaviour by shaping the flow of resources which determine access to opportunities or constraints on behaviour. These structures, however, may not necessarily conform to the conventional spatial container of context defined by administrative units of data availability (census tract, postal code, traditional neighbourhoods). The lived existence of people is constituted through the contextualization of social structures and relations in

everyday life. Limiting these experiences and relationships to a specific context will jeopardize the opportunity to consider more fully the spatial and dynamic processes characteristic to life and health status. In essence, there is a risk of divorcing geographic context from social context (Gatrell, 1997).

The manner in which social structure is associated with the geographical distribution of health status is also a by-product of what people do at particular locations. According to Giddens (1984) individuals structure time and space socially producing unique spatial configurations of context. This relational perspective of context acknowledges the ingredients of mobility and social networks in a recipe of daily routine. The product of these routinized activities can be represented as activity spaces which are geometric indicators of the subset of all locations an individual has had contact with as a result of her activities (Golledge and Stimson, 1997). Activities such as commuting to work, purchasing food and socializing with friends and relatives are important elements of an individual's activity space. Furthermore, there is evidence that as the types of activities vary over the lifecourse, so do the contexts relevant to the production of social structures, and health status. Individuals create their own spatial geography within the context that their lives have already opened for them.

Collectively, then, these theoretical developments regarding individual agency, social structure, and activity space provide a starting point for exploring the influence of context on health. Coupled with population health research that is beginning to show the "ecosocial" nature of the various and simultaneous influences of context upon health (Krieger, 2001), it can be seen how human agency is embedded in social structure that both guides and is

guided by the pursuits of everyday life. They also provide the foundation for the conceptual, methodological and empirical activities in the thesis, which investigated the value of alternatively-defined and operationally-functional boundaries for investigating the relationships between context and health status.

Innovation in Time-Location Measurement

Time-location information constitutes the basis for identifying individual activities, the dynamic interaction between individuals and their context, and provides the input required for the development of the healthscape. The locations of individuals over time are usually characterized using time-activity diaries, self-report data of individual activities measured at pre-specified time intervals. Diaries suffer two obvious shortcomings: recall is difficult and sometimes inaccurate, and the resolution of information (activity categories, time interval length) can be limited. The novel component of this dissertation was the design and development of a wearable GPS data logger to attain high-resolution, time location data, and to establish a general framework for evaluating performance characteristics. Although several studies have employed commercially-available or custom designed wearable GPS data loggers to validate time-activity diaries or to improve exposure assessment models in environmental epidemiological investigations, wearable GPS has not been explored previously for measuring contexts relevant to health status.

The findings from the development and testing of the wearable GPS data logger are outlined in Chapter 3 (Rainham et al., 2008). A wearable and unobtrusive GPS data logging device was designed and constructed to allow for

extended high-resolution positioning under typical urban conditions. The GPS device is configurable so that researchers can set logging frequency and GPS performance characteristics under a variety of dynamic conditions. Unlike devices used in previous research, the design characteristics of the GPS device allow for extended high resolution positioning under typical urban conditions little input or maintenance. The device can sample at 1 s intervals for approximately 70 h continuously before recharge, and there is no danger of approaching data storage limitations. Although comparison with similar devices is difficult due a lack of information about configuration settings and definitions about what constitutes wearability, the GPS device designed in this thesis can log more data more frequently for much longer periods.

The assessment of positional accuracy and inter-instrument precision was undertaken under a variety of stationary and dynamic conditions to simulate a variety of transport modes in a range of urban environments. The average static accuracy of the GPS device was 2.8 m (±0.4 m). This is a respectable result when compared to a range of 1.7 to 10 m reported in similar studies, and is fully acceptable for the generation of time-location data. Dynamic conditions present a challenge for human tracking. Accuracy was best under open-sky conditions for pedestrian and cycling transport modes. However, as urban density increased, automobile and public transit modes became more accurate. This difference is hypothesized to be a result of structural and material interference in built-up areas, also known as the urban canyon effect. Roads are further away from buildings than sidewalks, and interference tends to decrease as the distance from buildings increases.

The results provided evidence of the feasibility of tracking individual movements over extended periods of time. One reason why Hägerstrand's time geography concept has not infiltrated research on context and health may relate to past difficulties in measuring adequately individual space-time pathways. The development of wearable GPS provides a method to accurately locate and speculate on a variety of human activities. While some inference of activity can be garnered from knowledge of location, individual experience associated with context is difficult to discern. For example, a visit to the local pub might be beneficial to health; however, the individual may have been drinking to assuage stress or have been involved in an altercation, both of which may be detrimental to physical or mental health status. Thus researchers are left to make some assumptions as to how specific contexts are associated with health status.

Innovation in Operationalizing Context

Most studies of the relationship between context and health use administrative boundaries such as census tracts (or a similarly defined spatial representation of neighbourhood) to operationalize contexts relevant to the exploration of geographic differences in health status or behaviours. While there are some good reasons to adopt these geographies, little attention has been afforded to investigating whether they capture the dimensions of context associated with the routine activities of everyday life. A major assumption of much place and health research is that the only context relevant to health is close to home. This assumption becomes less salient for individuals whose routine activities are more geographically dispersed. The ability to collect accurate, high-resolution (spatial and temporal) data using GPS data logging

provides the opportunity to 1) develop a unique set of geographies derived from time-location data, and 2) compare these geographies with traditional spatial units such as the census tract.

This was the focus of empirical research conducted in Chapter 4 in the thesis as a preliminary investigation of the proposed comparison. Using a cross-sectional survey from a randomly-selected sample of adults (≥ 18 yrs) in the geographic urban neighbourhoods of Halifax (n=53), supplemented by almost 10,000 hours of GPS time-location information, the research sought to determine how objectively-measured boundaries of context compared with census tracts – a commonly used boundary in place and health research. The results were generated through the application of techniques from spatial ecology and health geomatics to individual-level space-time information; these techniques were used to generate a set of 'healthscapes' or boundaries suitable for analyzing the influence of context on health.

In particular, the GPS data suggest a significant portion (30%) of an individual's time is spent outside the residential census tract, or what is customarily interpreted to be the 'neighbourhood'. For example, on average participants traversed 26 census tracts over a seven day period, with 95% of all activities occurring in a geography that encompassed approximately 13 census tracts. Furthermore, healthscape morphology among participants from the same census tract differs significantly among the participants and from the morphology of their residential census tract. In effect, the residential census tract represents inadequately the actual activities and space-time patterns of people, even those from the same census tract. Other variables that were linked

to features of an individual's healthscape were consistent with the population health perspective, and included income, employment, age, and health status.

A major finding is that the amount of time spent outside of the residential census tract as well as the characteristics of healthscape are weakly to moderately associated with compositional aspects of the population under study. When faced with a dearth of information about the appropriate geographical scale of context and health analysis, researchers may explore the use of individual determinants of health as indicators of the strength of contextual influence.

The strength of the correlation between contextual measures of material deprivation and social interaction potential for census and healthscape geographies decreases as an increase in the actual number of individual activities is taken into account. Approximately 40 to 60% of census tract-level variability in these measures is accounted for by the kernel density estimate (KDE95) polygons which are the most accurate geographical representation of participant activities. Using census tract geography will mis-estimate actual values of material deprivation and social interaction potential. In addition, these findings bring attention to the need for researchers to be conscious of the influence of scale in context and health analysis. They also suggest that the development of 'healthscapes' geography would prove useful in testing how contextual predictors vary with health status or other outcomes at different scales.

Regression modeling was used to compare the influence of contextual measures on physical, mental and self-reported health status after controlling for individual-level health determinants at census and healthscape geographies.

Age and household income were modestly predictive of physical and self-reported health status. Individual perceptions of neighbourhood quality and household income were modestly to weakly predictive of mental health status. In addition to individual level predictors, the contextual measure of material deprivation at the KDE95 healthscape geography consistently explained additional variation (2-3%) in physical and self-reported health status. Sociability at the census tract and minimum convex polygon (MCP) explained an additional 3-4% of the variance in self-reported health status. However this result is difficult to interpret as there was no contribution of sociability at these geographies for other health outcomes. Healthscape geographies are fundamentally not comparable morphologically such that the results are likely to be the result of simple random measurement error. In some cases the value of the model fit decreased indicating that the additional of contextual measures do not improve prediction over the mean model. Although preliminary, these findings suggest that incorporating actual measures of individual space-time activities may improve the ability to detect the influence of contextual measures on self-reported health status, even after consideration of individual-level health determinants. They are also supportive of the idea that relationships between measures of context and health are dependent on the variables chosen as well as the scale of analysis.

Limitations and Threats to Validity

The results of this dissertation need to be considered in the context of the potential for methodological limitations. First, several weaknesses may arise from data imperfections. Time-location information derived from wearable GPS

varies in accuracy according to the characteristics of the built environment and operational status of the satellite network. Equipment problems and non-compliance meant that complete samples were not collected for each participant. Bias may be introduced, albeit with the potential to be random, if these data were not available at consistent times across the complete sample.

Second, the cross-sectional analysis in Chapter 4 does not allow for inference about change. Land use and other characteristics of context change at relatively slow rates and may not be affected in the short-term by changes in human activities or travel behaviours. However, the relationships between human activities and context, from a time geographical perspective, are potentially bi-directional and thus constitute a potential threat to inferences regarding the causality of the relationships between characteristics of context, variations in values of health determinants, and ultimately health.

Third, construct validity is quite difficult to ascertain since the content of this work is relatively new and there is little theoretical guidance for operationalizing specific concepts. Construction of healthscape units, as well as the development of the compositional (material deprivation) and contextual indices (index of social interaction potential) is guided by key developments in the literature. For example, the index of material deprivation was developed for another study of the Halifax population at a different level of geography. The same variables and statistical analysis used in the construction of the index was applied to census tract level geography in this study.

Fourth, external validity is limited at the geographical level given the single study location and very small sample size. The majority of data was collected in the Spring through to Fall months and not at all in Winter.

Seasonal influences would likely modify the number of activities identified, as well as the spatial extent of activities.

Future Research Directions

This thesis has made several theoretical and methodological contributions in an area of population health research concerned with estimating the influence of place on health. The thesis comprises a series of studies that have provided a solid foundation for more detailed and larger scale evaluations of individual space-time patterns and the development of alternative strategies for operationalizing context in population health research. According to a report by the Canadian Population Health Initiative (CIHI, 2005), research of place and health should move away from absolute definitions of context (boundaries) toward a methodology through which neighbourhood can be defined.

The concept of context that includes those characteristics of one's surroundings necessary for the production of health is a major contribution to the determinants of population health. The notion of contextual health determinants describes a set of resources and mechanisms by which influences beyond those of the individual might manifest in human health, and possibly in the differential geographical distribution of health status. Place is very much a central theme in population health, and health geographers are well-placed to contribute to this work, particular if attention is devoted to work on the geographies of context and contextual indicators of health.

The following proposes several opportunities for expanding the role of GPS and geomatics for use in future health studies. First, the wearable GPS

data logger constitutes the first step in a path towards the development of wearable multi-sensor devices with applications in many other fields, including environmental epidemiology, disability and obesity research, psychology, physiology and many others. For example, a recent experimental pilot project linked the wearable GPS devices developed in this dissertation with wearable air quality monitors to develop a comprehensive model of fine particulate air pollution exposure in indoor and outdoor environments at 15 sec intervals over a 48-h period (Gibson et al., 2008). The devices are also being used in concert with accelerometers to evaluate the association between caloric expenditure and characteristics of the built environment. Additional sensors to measure physiological response would advance the ability to measure the relationships between specific exposures and changes in health status among known locations.

Several authors have proposed conceptual frameworks for the study of place and health relationships (Cummins et al., 2007; Frolich et al., 2001; Macintyre et al., 2002; Parenteau et al., 2008), and there have been repeated calls to develop spatial boundaries that reflect the multiplicity of dimensions that operate within and outside of these boundaries. The methods developed in this thesis could be used to explore the spatial and temporal attributes of dimensions of place that are theorized to influence health. Individual healthscapes can be reduced to focus on selected activities determined to be beneficial or detrimental to health. Overlapping healthscapes could be analyzed to identify locations of social interaction. A healthscapes approach could also be used to explore the influence of mobility as a health determinant or as a mediating factor in the relationship between context and health. Several space-

time activity datasets have been developed for transportation research and could be assessed for their usefulness in place and health studies.

The cumulative impact of context on health should be investigated longitudinally, preferably with larger samples and across a diversity of locales, and supported with qualitative inference. The centrality of the cumulative impact of context over the lifecourse has important implications. This thesis hypothesized, and provided preliminary evidence of an association between the size of contextual influence and age; some people are more place-bound than others and this observation may be a function of age or stage in the lifecourse.

The sample size was small in comparison to many place and health studies, although large for studies where time-location of participants is directly measured. Qualitative approaches would be tremendously useful in teasing out the manifestation of contexts that are more or less important to people. It is the quality of the context, and the type of activity pursued there, that are most influential to health. Space-time location data should be combined with qualitative information about the aspects of context more or less relevant to health. Features of context reported to be of value can be assessed objectively to evaluate whether they form a part of an individual's actual experience, or whether they exist as a desirable attribute of context that may or may not influence health status.

Similar studies to the work in this thesis should be performed in other locations and conditions. Ultimately the space-time activities of people are constrained both by individual characteristics as well as the design of the environment they live in. On reflection it is quite remarkable to visualize the influence of street networks in the patterning of individual activities. Places

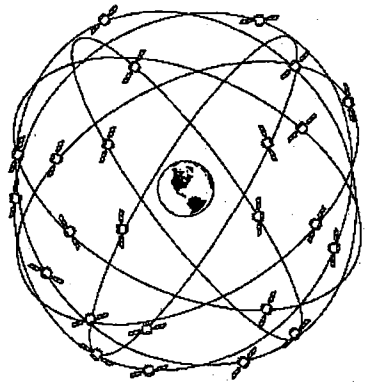
characterized by a variety of development forms should be explored as potential research locations.

Conclusions

There is increasing interest both conceptually and empirically in elucidating the nature of the relationships between context and health. The importance of GPS tracking and modeling for capturing individual space-time patterns was demonstrated in this study through the development of the healthscapes approach. GPS, GIS, and other components of health geomatics will become requisite tools for population health research concerned with context as a determinant of health. Visualization and analysis of individual space-time patterns yields insight into the geography of context currently lacking in place and health research. A healthscapes or similar approach has a great deal of potential for future research, and such work, with careful conceptualization and theoretically-informed empirical analyses could make a valuable contribution to population health research.

Chapter 6

Contributions of Collaborators



Contribution of Collaborators

This section of the dissertation provides a statement of contributions of collaborators written in accordance with the guidelines of the Faculty of Graduate and Postdoctoral Studies at the University of Ottawa (2006). Contributions include those who were involved as part of the research team as well as those who provided engineering and technical support.

Research Team Members

Daniel Rainham BES, MSc, PhD(c) conceived of, participated in, and led all aspects of the research study as part of the fulfillment of the degree of Doctorate in Philosophy at the University of Ottawa. Collaborators were selected to provide a transdisciplinary perspective on the newly emerging field of context and health research. Several academic disciplinary perspectives and their associated perspectives, including social epidemiology, geography, biostatistics and electrical engineering, were brought together in an integrated fashion to develop and advance issues in place and health research.

Daniel Rainham (DR) has expertise in population and environmental health, geographic information systems, global positioning systems for human tracking, and health geomatics. In addition to completing doctoral studies in the Population Health Program at the University of Ottawa, he is a research associate with the McLaughlin Centre for Population Health Risk Assessment at the University of Ottawa, an Honourary Research Fellow in the Faculty of Science at Dalhousie University, and has been appointed as the Elizabeth May Chair in Human Health and Sustainability in the Faculty of Science at Dalhousie University beginning January, 2009. DR received a three-year

doctoral research award from the Canadian Institutes of Health Research (CIHR, Population health), and a Scholarship of Excellence from the University of Ottawa.

Thesis committee members, Professors Daniel Krewski MHA, PhD (DK), Ian McDowell PhD (IM), and Mike Sawada PhD (MS), collaborated in the development of the proposal, provided consultation throughout the research process, participated in the analysis and interpretation of the findings, and contributed to the intellectual content of the drafted and final manuscripts. Brian Liekens (BL) contributed engineering and design assistance with the development and manufacture of the custom wearable global positioning system data logger (Table 6.1).

Table 6.1
Summary of Author Contributions

	Chapter 1 Introduction	Chapter 2 Conceptualizing the healthscape	Chapter 3 Developing a wearable GPS	Chapter 4 Operationalizing the healthscape	Chapter 5 Integrated discussion
Conceive and design	DR	DR DK IM MS	DR MS BL DK IM	DR IM DK MS	DR
Data collection	DR	DR	DR	DR	DR
Analysis and interpretation	DR	DR IM DK MS	DR MS DK IM	DR IM MS DK	DR
Draft manuscript	DR	DR	DR	DR	DR
Manuscript revision	DR IM DK MS	DR IM DK MS	DR MS IM DK	DR IM DK MS	DR DK IM MS
Approval for publication	DR DK	DR IM DK MS	DR DK IM MS BL	DR DK IM MS	DR DK
Responsibility for overall content	DR	DR	DR	DR	DR

Daniel Krewski has a doctorate in biostatistics, holds a NSERC/SSHRC/McLaughlin Chair in Population Health Risk Assessment and has expertise in population and environmental health risk assessment, biostatistics, risk management and health policy. He is a professor at the University of Ottawa in the Faculty of Medicine (Department of Epidemiology and Community Medicine) and Faculty of Science (Department of Mathematics and Statistics), a Principal Scientist at the Institute of Population Health, and Director of Samuel L. McLaughlin Centre for Population Health Risk Assessment.

Ian McDowell, a social epidemiologist, holds a doctorate in Community Medicine, and has research expertise in health measurement, theoretical epidemiology, dementia and population health methodologies. He is a full professor at the University of Ottawa in the Faculty of Medicine (Epidemiology and Community Medicine) and a Principal Scientist at the Institute of Population Health.

Mike Sawada, a geomatician with a degree in geography, holds the 2006 Julien M. Sciecz Award from the Canadian Association of Geographers and 2007 Young Researcher of the Year from his faculty at the University of Ottawa and has expertise in spatial analysis. He is an associate professor at the University of Ottawa in the Faculty of Arts and is a professor within the Ottawa-Carleton Geoscience Center, Faculty of Graduate and Postdoctoral Studies and Institute of Environment.

Brian Liekens is a mechanical and electrical technician at Dalhousie University in the Faculty of Engineering (Civil and Resource Engineering).

Additional consultation was obtained from Dr. Sean Doherty, an associate professor of geography at Wilfred Laurier University and an expert in human activity/mobility patterns and tracking methods. Research assistants, Gavin King, Sara Pullen, and Jennifer Jones participated in pilot testing and deployment of the GPS data logger.

Manuscript Co-authorship

The criteria for authorship and for the manuscripts within this dissertation are based on the authorship guidelines and recommendations of the International Committee of Medical Journal Editors (2007). All members of the research team contributed to each manuscript and qualified as authors according to the following criteria:

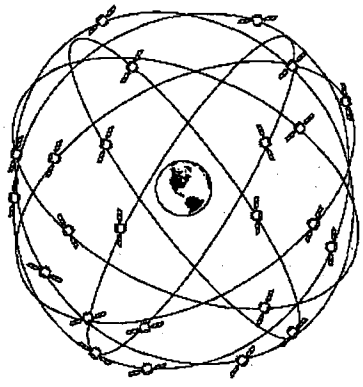
1) substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data;
2) drafting the article or revising it critically for important intellectual content; and,
3) final approval of the version to be published (International Committee of Medical Journal Editors, 2007).

Overall, DR conceived of the study, designed the study in collaboration with co-authors (DK, IM, MS), recruited participants, designed the data collection device in collaboration with BL, collected the data, managed the data, carried out the quantitative and statistical analysis in collaboration with the co-authors, drafted the manuscripts, re-drafted the manuscripts in collaboration with the co-authors (IM, DK, MS), and was responsible for the overall management of the

study. Co-authors approved the final manuscripts with specific contributions detailed in Table 6.1.

Chapter 7

Common References and Appendices



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HEALTH SCIENCES AND SCIENCE RESEARCH ETHICS BOARD

CERTIFICATION OF ETHICS APPROVAL

This is to certify that the University of Ottawa Health Sciences and Science Research Ethics Board (REB) examined the application for extension of ethics approval for the research project The Halifax Healthscapes Study (file H 07-06-02) submitted by Daniel Rainham and supervised by Daniel Krewski of the Institute of Population Health.
This project received initial ethics approval on November 8, 2006 by the REB as meeting appropriate ethical standards set out in the Tri-Council Policy Statement and in the Procedures of the University of Ottawa Research Ethics Boards. The University of Ottawa REB members accordingly gave it a one-year extension of ethics approval. This ethics renewal certification is retroactive to November 8, 2007 and valid until November 8, 2008.

Germain Zongo
Protocol Officer for Ethics in Research
For Dr. Daniel Lagarec, Chair of the
Health Sciences and Science REB

December 13, 2007
Date

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LETTER OF INFORMATION AND CONSENT

The Halifax Healthscapes Study

Dr. Dan Krewski, Ph.D.
McLaughlin Centre for Population Health Risk Assessment
One Stewart Street, Ottawa, Ontario, K1N 6N5

Dear Participant,

As a professor at the University of Ottawa at the Institute of Population Health, I supervise Daniel Rainham, a Ph.D. student who is conducting a study to investigate the relationships between people's health and their daily activity patterns. The objective of this study is to evaluate your perceptions of quality of life, physical and psychological well-being, and the relationships and contacts you have with others and with your community in relation to your daily activities. You are receiving this letter of information based on previous indication of your willingness to participate. As part of the study you will be asked to complete a questionnaire and wear a portable global positioning system for a one-week period. Your involvement will consist of:

1. Completing a written questionnaire of approximately 30 minutes in length. The questionnaire consists of two sections with questions about your neighbourhood and your perceived physical and mental health, The study will be conducted in English only.

2. Wearing a portable GPS data logger on a daily basis for up to a one-week period. The GPS unit will only be worn during the daytime and records you position using satellite technology. Should you not want your location to be known you will be able to turn off the unit at any time. These locations will help us to understand your travel patterns in the Halifax area over a specific period of time. The GPS unit poses no health risk.

The information collected in the study will remain strictly confidential. Anonymity will be assured by assigning a number to your file so that your name will not appear on any questionnaire or data file. Furthermore, completed questionnaires and any maps created from the GPS data will be stored in a locked filing cabinet of Dr. Krewski for a period of ten years following the publication of the results after which they will be destroyed. Only the research team, which consists of one Ph.D. student who will conduct the questionnaire and administer the GPS data collection, and three faculty members, Drs. Mike Sawada and Ian McDowell, and myself, Dr. Dan Krewski, will have access to the codes and data. You will be able to receive a summary of the findings of this research, which will be available in August 2008.

Benefits of this study: Recent research has shown that our health is not only related to personal lifestyle, such as the food we eat or our yearly income, but also to the characteristics of the neighbourhood(s) within which we conduct our daily activities. This study affords an excellent opportunity to link health and neighbourhood information provided by the questionnaire to the spatial and temporal patterns detected by the wearable global positioning system. You will see a map of your activity patterns over the week that you wore the GPS unit. The results from this research will be useful for municipal planners, decision-makers and population health researchers who require input on how best to design healthy and viable communities. Participating in this study could also be a valuable and rewarding learning experience for you!

Potential risks involved: There is minimal risk involved in this study. Your involvement will consist of sharing personal information about your everyday life. If you regret having disclosed personal information in the questionnaire or as part of the GPS data collection process, that information will be excluded from the study and will not be reported in any form of communication. In fact, you will be able to review a map of your daily and weekly time activity patterns for authentication purposes and will be allowed to remove or modify any information you think does not accurately reflect your experience.

The results of this study will be presented at conferences or published in academic journals but your name will not be mentioned at any time. You are under no obligation to participate and are free to withdraw from the project at any time.

Consent: I, _____, agree to participate in the above research study conducted by Daniel Rainham of Environmental Programmes in the Faculty of Science at Dalhousie University, which research is under the supervision of Dr. Daniel Krewski.

Should you have any questions regarding this research project, please contact Daniel Rainham the Study Coordinator at: tel: 902.494.8091, e-mail: daniel.rainham@dal.ca, Environmental Programmes, Faculty of Science, Dalhousie University. Alternatively you may contact Dr. Dan Krewski at: tel: 613.562.5381, fax 613.562.5380, e-mail: dkrewski@uottawa.ca McLaughlin Centre for Population Health Risk Assessment, University of Ottawa.

If you have any questions with regards to the ethical conduct of this study, you may contact the Protocol Officer for Ethics in Research of the University of Ottawa, Tabaret Hall, 550 Cumberland Street, Room 159, Ottawa, ON K1N 6N5, tel: 613.562.5841, email: ethics@uottawa.ca.

There will be two copies of the consent form, one of which is mine to keep.

Participant's signature: _____ Date:_____

Researcher's signature: _____ Date: _____

2007 Halifax Healthscapes Survey

Thank you for taking the time to complete this survey. The purpose of the study is to collect information about neighbourhoods, social interactions and health status.

Please answer all questions as accurately as possible and to the best of your knowledge. Your answers will be kept strictly confidential and used only for statistical purposes so that your anonymity is guaranteed. While participation is voluntary, your cooperation is important to ensure that the information collected in this survey is as accurate and as comprehensive as possible.

Please write your residential address here:

Civic number

Apartment or Suite #

Street Name (include suffix)

City

Postal Code

DATE:

D D M M Y Y Y Y

ADMIN ID:

GPS ID:

Please turn the page and proceed with the questionnaire. Thank you again for your participation.

We would like to begin by asking you about the neighbourhood you live in.

1. **What are the most important things you <u>like</u> about the neighbourhood where you live?**

_____

_____

_____

_____

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2. **What are the most important things you <u>dislike</u> about the neighbourhood where you live?**

_____

_____

_____

_____

---

3. **If there is a name for the area or neighbourhood that you live in, please write it below:**

_____

---

4. **How long have you been living in your neighbourhood?**

_____(years)

☐ don't know

---

5. **How long have you been living in Halifax?**

_____(years)

☐ don't know

---

6. **Many aspects of a person's neighbourhood contribute to their quality of life. We would like to know what you think about the neighbourhood you live in.**

How satisfied are you with the following aspects of your neighbourhood?
(Please mark the most appropriate choice)

	Very satisfied	Satisfied	Neither satisfied nor dissatisfied	Dissatisfied	Very dissatisfied
a. Parks and green space	○ 1	○ 2	○ 3	○ 4	○ 5
b. Amount of traffic	○ 1	○ 2	○ 3	○ 4	○ 5
c. Street lighting	○ 1	○ 2	○ 3	○ 4	○ 5
d. Police protection	○ 1	○ 2	○ 3	○ 4	○ 5
e. Recreation facilities	○ 1	○ 2	○ 3	○ 4	○ 5
f. Personal safety	○ 1	○ 2	○ 3	○ 4	○ 5
g. Environmental quality	○ 1	○ 2	○ 3	○ 4	○ 5
h. Walkability	○ 1	○ 2	○ 3	○ 4	○ 5
i. Accessibility to amenities	○ 1	○ 2	○ 3	○ 4	○ 5
j. Your neighbourhood as a whole	○ 1	○ 2	○ 3	○ 4	○ 5

7. **Sometimes neighbourhood safety conditions cause people to adjust their normal routines (for example, they may stay inside at night). Do safety conditions in your neighbourhood cause you to adjust the activities you'd like to be doing?**

- **A lot** ☐
- **Somewhat** ☐
- **A little bit** ☐
- **Not at all** ☐

---

8. **In general, how friendly are the people in your neighbourhood? Would you say they are:**

- **Very friendly** ☐
- **Friendly** ☐
- **Unfriendly** ☐
- **Very unfriendly** ☐
- **I don't know** ☐

To help us understand the quality of life in a community, we would like to find out how you have been feeling lately and to ask about your health in general.

9. **In general, would you say your health is:**

- **excellent** ☐
- **very good** ☐
- **good** ☐
- **fair** ☐
- **poor** ☐

---

10. Compared to one year ago, how would you rate your health in general now?

- **Much better than one year ago** ☐
- **Somewhat better than one year ago** ☐
- **About the same as one year ago** ☐
- **Somewhat worse now than one year ago** ☐
- **Much worse than one year ago** ☐

The next section deals with another way of measuring health status. The following questions are about activities you might do during a typical day.

11. Does your health now limit you in participating in any <u>vigorous</u> activities such as running, lifting heavy objects, or participating in strenuous sports?

- **Yes, limited a lot** ☐
- **Yes, limited a little** ☐
- **No, not at all limited** ☐

---

12. Does your health now limit you in participating in any <u>moderate</u> activities such as moving a table, pushing a vacuum cleaner, bowling, or playing golf?

- **Yes, limited a lot** ☐
- **Yes, limited a little** ☐
- **No, not at all limited** ☐

---

13. Does your health now limit you in lifting or carrying groceries?

- **Yes, limited a lot** ☐
- **Yes, limited a little** ☐
- **No, not at all limited** ☐

---

14. Does your health now limit you in climbing <u>several</u> flights of stairs?

- **Yes, limited a lot** ☐
- **Yes, limited a little** ☐
- **No, not at all limited** ☐

---

15. Does your health limit you in climbing one flight of stairs?

- Yes, limited a lot ☐
- Yes, limited a little ☐
- No, not at all limited ☐

---

16. Does your health now limit you in bending or kneeling or stooping?

- Yes, limited a lot ☐
- Yes, limited a little ☐
- No, not at all limited ☐

---

17. Does your health now limit you in walking more than one kilometre (or one mile)?

- Yes, limited a lot ☐
- Yes, limited a little ☐
- No, not at all limited ☐

---

18. Does your health now limit you in walking two or more blocks?

- Yes, limited a lot ☐
- Yes, limited a little ☐
- No, not at all limited ☐

---

19. Does your health now limit you in walking one block?

- Yes, limited a lot ☐
- Yes, limited a little ☐
- No, not at all limited ☐

---

20. Does your health now limit you in bathing and dressing?

- Yes, limited a lot ☐
- Yes, limited a little ☐
- No, not at all limited ☐

The following set of questions deals with potential physical and/or emotional problems with your work or regular daily activities.

21. During the past 4 weeks, have you had any of the following problems with your regular daily activities as a result of your physical health?
(Please mark the most appropriate value)

	Yes	No
a. As a result of your physical health have you cut down on the amount of time you spent on work or other activities	○ 1	○ 2
b. As a result of your physical health have you accomplished less than you would like	○ 1	○ 2
c. As a result of your physical health were you limited in the kind of work or other activities	○ 1	○ 2
d. As a result of your physical health have you had difficulty performing the work or other activities (for example, it took extra effort)	○ 1	○ 2

---

22. During the past 4 weeks, have you had any of the following problems with your regular daily activities as a result of your emotional health?
(Please mark the most appropriate value)

	Yes	No
a. As a result of your emotional health have you cut down on the amount of time you spent on work or other activities	○ 1	○ 2
b. As a result of your emotional health have you accomplished less than you would like	○ 1	○ 2
c. As a result of your emotional health were you limited in the kind of work or other activities	○ 1	○ 2
d. As a result of your emotional health have you had difficulty performing the work or other activities (for example, it took extra effort)	○ 1	○ 2

23. **During the past 4 weeks, to what extent has your physical or emotional health interfered with your normal social activities with family, friends, neighbours, or groups?**
(Please tick **one** box.)

- **Not at all** ☐
- **Slightly** ☐
- **Moderately** ☐
- **Quite a bit** ☐
- **Extremely** ☐

---

24. **How much pain have you had during the past 4 weeks?**
(Please tick **one** box.)

- **None** ☐
- **Very mild** ☐
- **Mild** ☐
- **Moderate** ☐
- **Severe** ☐
- **Very Severe** ☐

---

25. **During the past 4 weeks, how much did pain interfere with your normal work?**

(Including both work outside the home and housework)?
(Please tick **one** box.)

- **Not at all** ☐
- **Slightly** ☐
- **Moderately** ☐
- **Quite a bit** ☐
- **Extremely** ☐

---

26. **These questions ask you about how you have been feeling <u>during the past 4 weeks</u>. Please give the one answer that is closest to the way you have been feeling for each item.**
(Please mark the most appropriate choice)

	All of the Time	Most of the Time	Some of the Time	A Little of the Time	None of the Time
a. Did you feel full of life?	○ 1	○ 2	○ 3	○ 4	○ 5
b. Have you been a very nervous person?	○ 1	○ 2	○ 3	○ 4	○ 5
c. Have you felt so down in the dumps that nothing could cheer you up?	○ 1	○ 2	○ 3	○ 4	○ 5
d. Have you felt calm and peaceful?	○ 1	○ 2	○ 3	○ 4	○ 5
e. Did you have a lot of energy?	○ 1	○ 2	○ 3	○ 4	○ 5
f. Have you felt downhearted and blue?	○ 1	○ 2	○ 3	○ 4	○ 5
g. Did you feel worn out?	○ 1	○ 2	○ 3	○ 4	○ 5
h. Have you been a happy person?	○ 1	○ 2	○ 3	○ 4	○ 5
i. Did you feel tired?	○ 1	○ 2	○ 3	○ 4	○ 5

27. How TRUE or FALSE is <u>each</u> of the following statements for you?

(Please mark the most appropriate value)

	Definitely true	Mostly true	Don't know	Mostly false	Definitely false
a. I seem to get sick a little easier than other people.	○ 1	○ 2	○ 3	○ 4	○ 5
b. I am as healthy as anybody I know.	○ 1	○ 2	○ 3	○ 4	○ 5
c. I expect my health to get worse.	○ 1	○ 2	○ 3	○ 4	○ 5
d. My health is excellent.	○ 1	○ 2	○ 3	○ 4	○ 5

---

28. Presently, would you describe yourself as:

- **Very happy** ☐
- **Somewhat happy** ☐
- **Somewhat unhappy** ☐
- **Very unhappy** ☐
- **No opinion** ☐

---

29. Do you smoke tobacco (cigarettes or cigars)?

Yes ☐ **If yes, how many do you regularly smoke in a day?** ☐☐

No ☐

Sometimes the kind of work people do can contribute to their quality of life. In the next few questions we would like to know a few things about your job.

30. What is your current employment situation?

- **Employed, full-time** ☐
- **Employed, part-time** ☐
- **Unemployed** ☐
- **Homemaker** ☐
- **Student, full-time** ☐
- **Other (please specify)** ☐ _____

The questionnaire is almost over. One thing that contributes to quality of life is an affordable neighbourhood setting. We'd like to know more about affordability in your neighbourhood, so we are asking that you tell us a bit about yourself and your income. As we said before, we will not ask you to provide your name, and all information you provide will be kept confidential. First, could you please tell us:

31. What is your main occupation?

_____

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32. Please check all that apply:

- **Female** ☐
- **Male** ☐
- **Transgendered/Transsexual** ☐

---

33. **What is your marital status?**

- Married ☐
- Living with partner ☐
- Widowed ☐
- Divorced ☐
- Separated ☐
- Single – never married ☐

Other (specify) _____

---

34. **What is the highest level of education you have completed?**

- Some high school ☐
- Completed high school ☐
- Trade certificate or training from vocational school ☐
- Diploma or certificate from community college ☐
- Some university ☐
- University degree ☐
- Post-graduate education ☐

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35. **In what year were you born?**

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36. **What was your approximate household income from all sources in 2005?**

- $0 to $15,999 ☐
- $16,000 to $29,999 ☐
- $30,000 to $39,999 ☐
- $40,000 to $49,999 ☐
- $50,000 to $59,999 ☐
- $60,000 to $69,999 ☐
- $70,000 or more ☐

37. **How many adults (persons 18 years of age or older) contribute to your approximate household income?**

☐☐ **adults**

---

38. **What is the best estimate of your total personal income, before taxes or any deductions, from all sources in the past 12 months?**

$ ☐☐☐☐☐☐☐☐

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39. **Is there anything you would like to add about your quality of life or your neighbourhood?**

_____

_____

_____

_____

_____

_____

Thank you very much for your cooperation. The information you have provided will be extremely valuable to researchers and policy-makers.

Please indicate below if you would like to receive further information about the study and the results once the study is complete.

Yes ☐ **No** ☐

Would you be willing to be contacted in the future if there are any concerns about the data you have provided or if further information is required?

Yes ☐ **No** ☐