Activity-Space Segregation: Understanding Social Divisions in Space and Time

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Introduction

Most of what we know about spatial segregation centers on where people live, yet many of the consequences we care about depend on where people spend time outside their homes (Matthews, 2011; Basta, Richmond, & Wiebe, 2010; Kwan, 2009). This paper addresses the problem by presenting a new theoretical and methodological framework for understanding systematic differences in the spaces people move through as they go about their daily activities—a phenomenon best described as activity-space segregation (Wong & Shaw, 2011).

Activity-space segregation is the separation of social groups in space and time, viewed at the spatial scale of neighborhoods and cities and the temporal scale of hours and days. It can be thought of as a three- or four-dimensional extension of residential segregation, with time added to the Cartesian axes of geographic space. Instead of considering individuals as points on a plane, the activity-space approach treats them as messy, irregular curves that extend over time, tracing circadian rhythms to and from their homes. By analyzing the paths of these curves, we can learn about interaction and barriers between groups of people, and between people and places, and about the role of movement itself in people's lives.

Activity-space segregation should be of great concern to social scientists and policy-makers because it is a mechanism through which ascriptive personal characteristics like race, ethnicity, and gender can come to exert huge influence on individuals' economic and social well-being. At the core of the problem is the fact that resources are distributed unevenly across space and time, making access to these resources dependent on the spatio-temporal distribution of people (cf. Fischer & Tienda, 2006; Massey, 1996). By ensuring that some groups will have less access to resources than others, activity-space segregation, much like residential segregation, threatens basic principles of justice and equality.

Moreover, also like its residential counterpart, activity-space segregation is a problem in which law and policy are deeply implicated. From "pass laws," separate public amenities, and other express constraints on racial mixing in apartheid-era South Africa (Breckenridge, 2005; Dugard, 1979) or the Jim Crow United States (Sandoval-Strausz, 2005; Woodward, 2002) to contemporary Saudi restrictions on female movement and gender mixing (Mtango, 2004; Mayer, 2000), even a quick glance around the world reveals a variety of obvious ways in which states produce and reinforce social divisions in space and time. Less obvious ways include police and military check-points, racial profiling tactics, public transportation networks, zoning laws, loitering laws, day worker laws, maternity leave and child care laws, curfews, the placement of walls, fences, roads, parks, and buildings, mortgage and lending policy, and the range of state action that limits or encourages private violence and discrimination. In this list, one can find policies responsible for the severe residential segregation that remains one of the major social problems facing the United States (D. Lichter, Parisi, & Taquino, 2011; Rothwell, 2011; Massey, Rothwell, & Domina, 2009; Ford, 1994; Massey & Denton, 1993). Some of these policies influence residential and activity-space segregation independently, and some influence activity-space segregation *through* their influence on residential segregation, since the latter shapes activity patterns by determining the places in which individuals start and end their days.

This relationship between residential segregation and daily activities is one reason why residential segregation is such an important area of investigation.[1] What social scientists measure when examining spatial relations is almost always residence (Ellis, Wright, & Parks, 2004), and often with the assumptions that a person's place of residence reveals information about the people around whom that person spends time, the parts of a city he or she visits, and the services, institutions, and jobs that are accessible. With these assumptions, we can rely on readily available residence data as a way to learn about what are really questions of activity-space. In doing so, however, we treat residence as a proxy for more dynamic facts of location and movement that remain hidden (Matthews, 2011). Although reasonably accurate in many cases, such assumptions ultimately depend on where the person spends time when not at home (Matthews, 2011; Basta et al., 2010; Kwan, 2009; Chaix et al., 2009; Entwisle, 2007).

Location and movement outside the home are much harder to measure than residence. Place of residence is a physical fact that remains fixed for extended periods of time and is likely to be remembered. It is also an administrative fact that is often recorded by government and private institutions. Location outside the home, in contrast, is more transitory and generally less likely to be remembered or recorded. Exceptions, of course, include socially significant places in which people spend time, such as work and school, which can be captured to varying degrees through surveys. For other places, gathering data can be more difficult, and often requires direct observation, time-space diaries, or transport systems analysis (Matthews, 2011; Basta et al., 2010; Ohnmacht, Maksim, & Bergman, 2009; Urry, 2007; Janelle, Klinkenberg, & Goodchild, 1998; Goodchild & Janelle, 1984). The increasingly common use of mobile phones, however, is beginning to open up new possibilities for studying location and movement because these devices leave traces of their approximate loca-

[1] Another reason is that place of residence is itself a critical factor in understanding a variety of social issues, from access to loans, parks and schools to housing quality, safety and political participation. "Residence in a municipality or membership in a homeowners association involves more than simply the location of one's domicile; it also involves the right to act as a citizen, to influence the character and direction of a jurisdiction or association through the exercise of the franchise, and to share in public resources" (Ford, 1994).

tions whenever used to place calls and they can record much more precise location estimates based on signals from GPS satellites, cellular towers, Wi-Fi routers and other electromagnetic transmitters (Palmer et al., in press; Ahas, 2011; Raento, Oulasvirta, & Eagle, 2009; Ahas & Mark, 2005; Asakura & Hato, 2004).

Although the quantity of available data on daily activity patterns is still far smaller than that on residence (and there are good reasons why this should and probably will remain so), it is now possible to gather enough data on these patterns to conduct meaningful segregation analysis. Palmer et al. (in press), Wong and Shaw (2011), and Toomet, Silm, Saluveer, Tammaru, and Ahas (2011) all take activitiy-space approaches to explore mobile phone and travel diary data on inter- and intra-group exposure. At the same time, however, theoretical and methodological development in this area is still at a very early stage. The present paper contributes by proposing a new framework within which to study activity-space segregation. The core of my framework is a set of indexes by which activity-space segregation in a given community may be quantified and meaningfully compared to that of other communities. Drawing on Torsten Hägerstrand's concept of space-time prisms (Hägerstrand, 1970), my approach incorporates time into traditional, static measures of evenness, exposure, concentration, and clustering (Massey & Denton, 1988), substituting three- or four-dimensional space-time units for the traditional indexes' two-dimensional areal units. In addition, I propose a set of modifications to these measures, some drawn from ecology, which may be used to augment the basic indexes and better address questions of social interaction, "habitat" use, and movement. For all of the proposed measures, the goal is to make it easier to understand not simply abstract spatial relations, but their social consequences and determinants.

I begin by placing this research in the context of the sub-disciplines on which it primarily builds: human ecology and time geography (Part 1). I then explore patterns, causes, and consequences of segregation, starting with the large body of empirical work on residential, school, and workplace segregation (Part 2). This exercise demonstrates the importance of the project, and serves as a starting point for designing and evaluating the proposed indexes. Next, I present and discuss the indexes and additional proposed measures (Part 3), and I demonstrate some of these by applying them to the full 2000 census population of non-Hispanic blacks and whites in Buffalo, New York, doing 8 hours of simulated random movement along the city and county road network, starting in their actual residential census tracts (Part 4). I conclude (Part 5) with a brief summary of the next steps to be taken in this research.

1 Linking Space and Time

The idea of activity-space segregation is grounded in an ecological perspective of society—one that seeks to understand social relations in their spatial context. The importance of this ecological perspective has long been apparent, even if at times neglected (Anderson & Massey, 2001). In his famous study of the African American community in 19th century Philadelphia, for instance, W.E.B. Du Bois explained how housing market discrimination, occupational requirements, social pressures and immigration led to the concentration of black homes in neighborhoods with inflated rents, overcrowded dwellings, poor sanitation, frequent crime, and rapid residential turnover (Du Bois, 1899). Spatial variation and relationships were at the core of the Chicago school sociologists' work in the 1920s, and gained renewed attention at the end of the century with the recognition that residential segregation continues to concentrate poverty, ensure unequal access to resources, and facilitate discrimination in other sectors (Anderson & Massey, 2001; Massey & Denton, 1993; Wilson, 1987).

This spatially-focused approach is bound up with the interdisciplinary field of human ecology, which views "collective life as an adaptive process consisting of an interaction of environment, population, and organization" (Hawley, 1986). Human ecology is concerned with the organization of human populations within their environments in terms of system-level growth and evolution and the formation of interdependencies between population members

(Hawley, 1986). Among other things, therefore, human ecology requires the linkage of spatial questions with temporal ones. It is a field in which the idea of activity-space segregation naturally finds a home.

Activity-space segregation also draws heavily from the related fields of time and behavioral geography. Activity space, in these fields, refers to the "locations within which an individual has direct contact as a result of his or her day-to-day activities" (Golledge & Stimson, 1997, p. 279). It is the component of the individual's overall environmental interaction that involves movement and direct contact, as opposed to communication. Without yet bringing in the substantive social implications of activity-space segregation, we can think of it abstractly as a matter of simply linking space with time. If we treat space as a two-dimensional Cartesian plane, the addition of time creates a three-dimensional object that Hägerstrand (1970) describes as the space-time aquarium. Whereas the individual on a Cartesian plane is represented by a point (see Figure 1), the individual in a space-time aquarium is represented by a curve, the shape of which depends on the individual's movements (see Figures 2 and 3). When the individual is immobile, his or her space-time path is a straight line parallel to the time axis (Figurue 2). When the individual moves, the path angles away from the time axis, with the slope and curvature depending on velocity and acceleration (Figures 3 and 4) (Kwan & Lee, 2004; Lee & Kwan, 2011; Kwan, 1999). The maximum angle between the individual's curve and the time axis depends on the individual's maximum velocity. No person can have a space-time path that is orthogonal to the time axis, as this would require infinite velocity, and the greatest slope we would expect for people in a city would be about 11 m/s (the average speed of a train).

One reason why Hägerstrand's idea is powerful is that it helps us understand how time constrains the spatial extent of our activities. If we know nothing about a person's movement and only know his or her location at one moment in time, we can construct two cones, one extending forward in time and one extending backward in time, within which physical

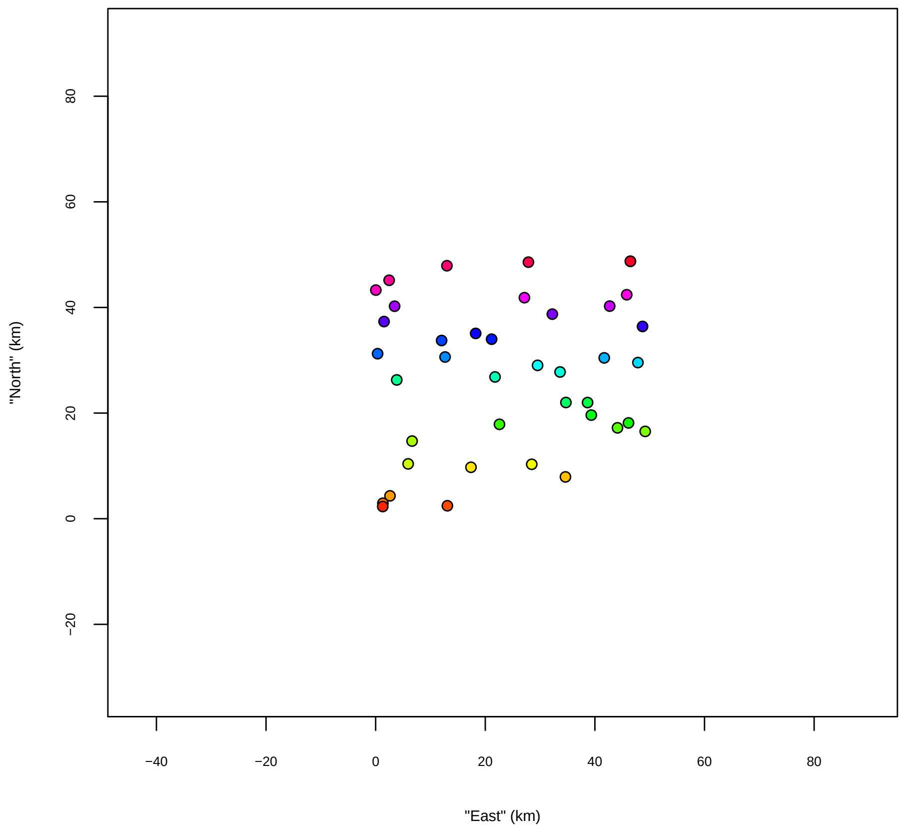

Figure 1 – Individuals represented on cartesian plane.

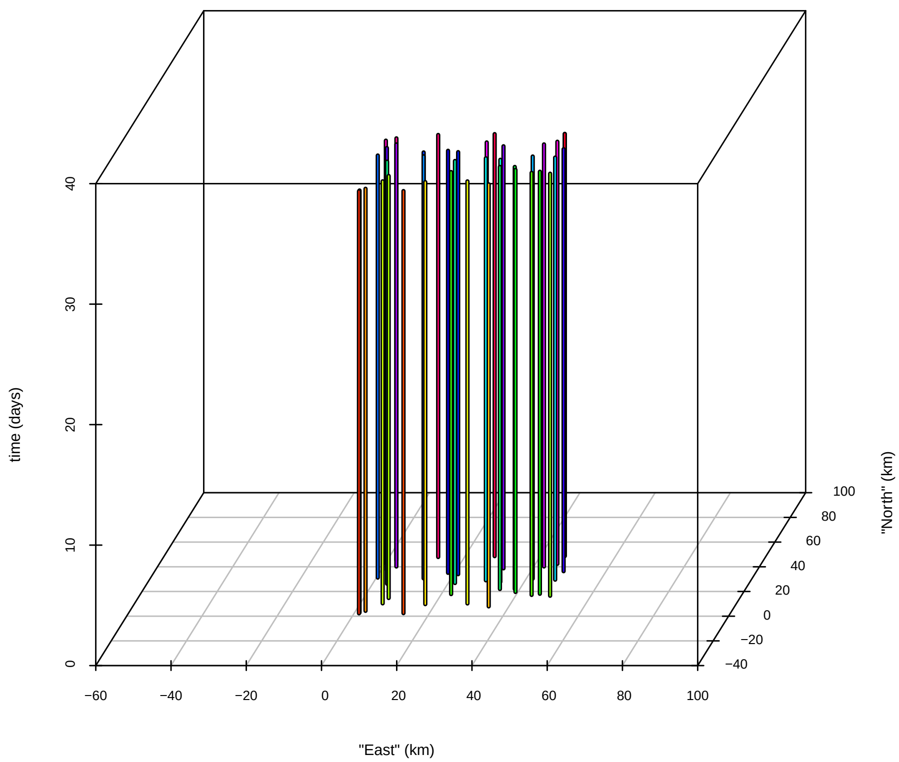

Figure 2 – Stationary individuals represented in space-time aquarium.

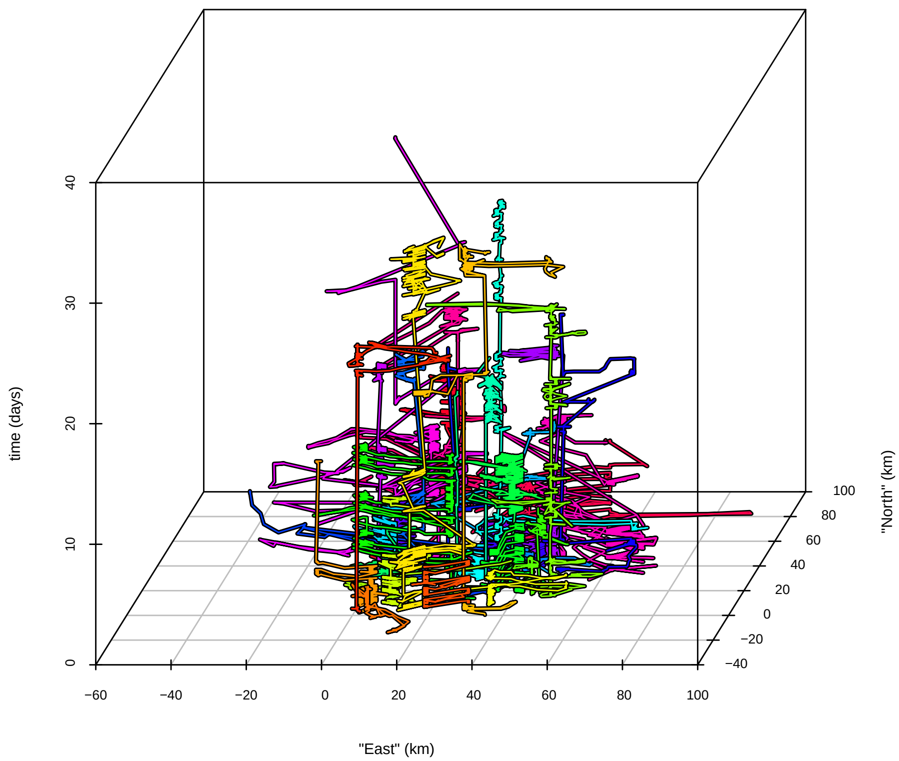

Figure 3 – Moving individuals represented in space-time aquarium. Curves are drawn from actual location data collected in the Human Mobility Project Pilot Study (Palmer et al. in press), but they have been transformed to protect participants' privacy and moved closer together in space for better comparison.

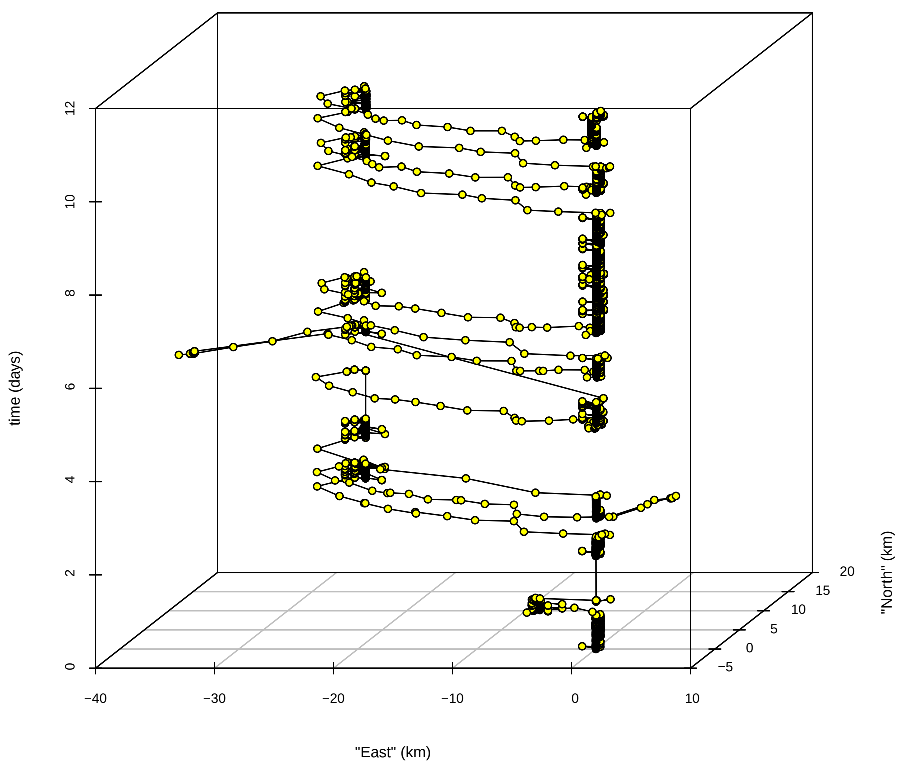

Figure 4 – The space-time path of one individual followed over 11.5 days during the Human Mobility Project Pilot Study (Palmer et al. in press). All locations have been transformed to protect privacy.

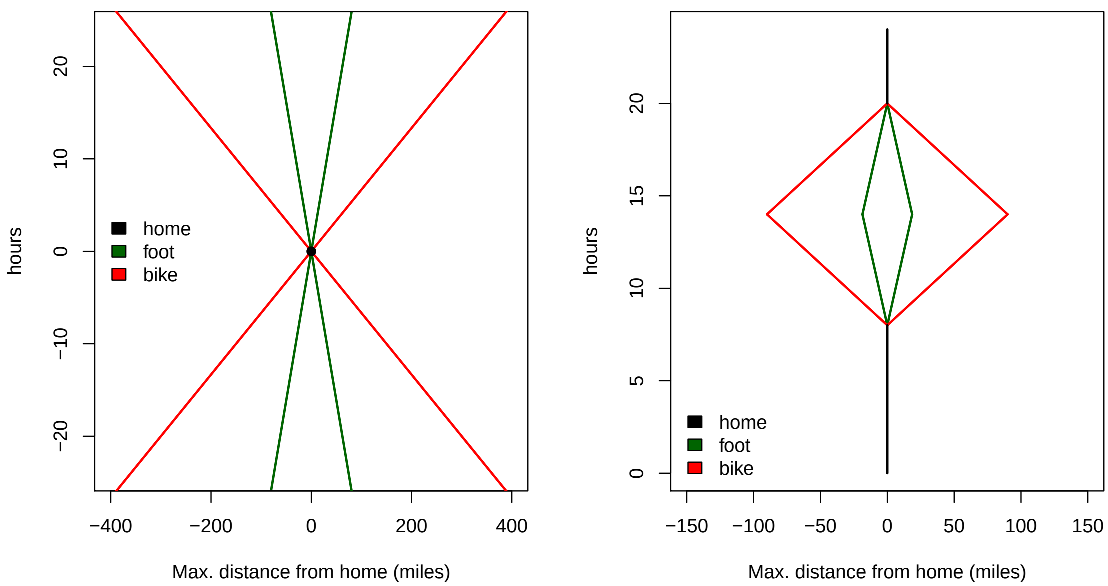

Figure 5 – Space-time boundaries for person traveling by foot and bicycle. Diagonal lines indicate outer limits of space-time path given maximum speed for each mode of transportation. Left panel shows possible locations in past and future given knowledge of location at time zero (present). Right panel shows space-time prism for one day with home constraints.

velocity constraints ensure that any future or past path must lie (Figure 5).[2] Moreover, if we now consider that people require some amount of sleep on a regular basis, and that they tend to take it in the same place, we see that each of the cones can expand only so far before it must contract back to the place of residence, becoming a straight line during the time when the person remains immobile at home (Figure 5). Hägerstrand called this the space-time prism. With more information about constraints and conduits, the space-time prism becomes increasingly messy, with notched edges where physical obstacles block the path, narrow spurs coming off the sides where vehicles are available, and smaller prisms growing from the ends of spurs.

Another value of Hägerstrand's approach is the way it helps us to visualize a number of important social phenomena that influence both residence and daily movement. For

[2]This is analogous to the famous light cone in Minkowski spacetime, as the concept is used in physics (Minkowski, 1908; Petkov, 2010).

example, women's disproportionate share of domestic obligations (Ellis et al., 2004; Kwan, 1999; Blair & Lichter, 1991) should appear as systematically smaller prisms due to greater time constraints. If we imagine the column of space-time prisms produced over multiple days for a person with fixed residence constraints, then a migration event is represented by a shift in the position of this column on the spatial axes. Incarceration is represented by a shift in the column, combined with shrinkage or elimination of the prisms depending on the conditions of confinement. Homelessness may be represented by frequent shifts in the column as a person moves between shelters, or by a breakdown of the column structure altogether.

The space-time aquarium and space-time prisms do not solve the problem of how to measure activity-space segregation, but they provide useful tools to which we we will return when constructing aggregate segregation indexes. Before doing so, however, it is important to set aside abstract geometry and consider the social significance of the phenomenon we are trying to measure, since it is not spatial measures themselves that we care about but, rather, their social content (Simmel, 1903).

2 Social Significance

Cynthia Wiggins was seventeen year old in 1995 when she was hit by a dump truck while trying to walk across a snowy seven-lane highway to reach her job in a suburban Buffalo mall. She had just gotten off the city bus she rode every day to work, a commute that required 50-minutes to transport her from her home in East Buffalo into in the adjacent suburb of Cheektowaga. Although charter busses from as far as Canada regularly stopped at the mall entrance to deliver shoppers, the owners of the mall had refused for the past eight years to allow Buffalo city busses to stop on mall property. Consequently, the city bus stop was 300 yards away, on the far side of a highway without sidewalks or a crosswalk. Wiggins had made it past eight-foot snowbanks and across six of the highway's seven lanes when the light changed and the truck hit her. She died after several weeks in a coma, leaving behind a four-month old son, a fiance, a father, and five siblings (Fisher, 2011; Barnes & Blackman, 1996).

Wiggins' life and the circumstances of her death illustrate some of the ways in which segregation manifests itself and is shaped by law and policy in contemporary American cities. Her death is exceptional but the other aspects of her case, including the difficulty and hazards of her commute, are not. They help to place the social significance of activity-space segregation in stark relief, providing an example of why it is a topic worthy of further study and helping inform our analysis of how to measure it. To ensure that our measures are able to capture and illuminate the socially significant content, it is important to consider what is already known about activity-space segregation, its causes, and its consequences. Wiggins is just one piece of the puzzle, but she serves as a good point of departure and a reference along the way.

2.1 Patterns and Determinants

Aggregate patterns of activity-space segregation are only just beginning to receive attention (Palmer et al., in press; Wong & Shaw, 2011; Toomet et al., 2011), but segregation across homes, schools and workplaces has been a topic of analysis for many years. We also know about the commuting problems faced by many people, like Wiggens, who live in poor central-city neighborhoods. From this information, we can begin to construct a more comprehensive picture of activity-space segregation. In discussing what is known about these patterns and their causes, I will focus on the United States.

Residential segregation is the area for which we have the most information. In the United States, residential segregation exists along lines of race, ethnicity, class, and ideology. Historically, the phenomenon has been dominated by the segregation of African Americans with respect to whites. At the level of census tracts, black-white residential segregation increased sharply during the 20th century, as blacks migrated from the rural South into urban areas where they found themselves packed into concentrated ghettos, particularly in the industrial cities of the North (Massey et al., 2009; Massey & Denton, 1993). The pattern of segregation that developed was, as Massey and Denton (1993) put it, "constructed through a series of well-defined institutional practices, private behaviors, and public policies by which whites sought to contain growing urban black populations." These initially included laws expressly prohibiting blacks from residing in certain neighborhoods[3] and restrictive private covenants limiting the sale of property according to the buyer's race.[4] They also included (1) outright violence, intimidation, and other forms of harassment, often tolerated or encouraged by state and local authorities, (2) urban development and public housing projects designed to reinforce barriers between black and white neighborhoods, often with federal funding (Massey

[3]The Supreme Court held such laws unconstitutional in *Buchanan v. Warley*, 245 U.S. 60 (1917), reasoning that restricting the rights of homeowners to sell to buyers of their choice constituted a deprivation of property, and thus distinguishing *Plessy v. Ferguson*, 163 U.S. 537 (1896), which remained intact for another 37 years.

[4]The Supreme Court held the judicial enforcement of such covenants unconstitutional in *Shelley v. Kraemer*, 100 U.S. 1 (1948), although such covenants continued to be employed beyond that year even without judicial enforcement (Massey & Denton, 1993; Jackson, 1985).

& Denton, 1993), and (3) discrimination in private housing and lending markets that was not only tolerated but encouraged by the Federal Housing Authority and other government agencies until the 1970s and that continues today in more hidden forms.[5] The result was that African Americans have faced more extreme and persistent levels of segregation than any other group in U.S. history (Massey & Denton, 1993), and until recently they were the only group facing hyper-segregation—high segregation along all five dimensions by which the phenomenon may be measured (Massey & Denton, 1989; Wilkes & Iceland, 2004).

Black segregation declined during the final third of the 20th century but remains significantly higher than that of other groups, and black hyper-segregation persists in many cities (Parisi, Lichter, & Taquino, 2011; Massey et al., 2009; Wilkes & Iceland, 2004). At the same time, in certain cities Latinos now face high segregation and, for the first time, hyper-segregation (D. T. Lichter, Parisi, Taquino, & Grice, 2010; Wilkes & Iceland, 2004), although average segregation of Latinos and of Asians nationwide has remained relatively stable in this period (Massey et al., 2009). As racial segregation begins to fade, however, class and, to some extent, ideological segregation have become increasingly pronounced (D. Lichter et al., 2011; Massey et al., 2009; Massey, 1996).

Buffalo is one of the U.S. cities in which black-white segregation remains most severe (Trudeau, 2006), and Cynthia Wiggins lived in one of the central city neighborhoods in which Buffalo's black residents are overwhelmingly concentrated. In 1990, 92% of the Buffalo Metropolitan Area's black residents lived in the central city, joined there by only 25% of the area's white residents (Trudeau, 2006). When Wiggins' bus crossed from East Buffalo into Cheektowaga, it was crossing not just an administrative boundary but a racial one as well, and that divide had come about in much the same way as had black-white segregation elsewhere in the country. In the period around Wiggins' death, the City of Buffalo had been accused of discriminating in its public housing and rental assistance programs in a manner

[5] Although such private discrimination was largely prohibited by the Fair Housing Act of 1968, the enforcement provisions of that Act were notoriously weak and studies continue to illuminate the persistence of private housing discrimination (Massey, 2011; Turner, Ross, Galster, & Yinger, 2002; *The Future of Fair Housing*, 2008).

designed to keep blacks out of the suburbs.[6] There was also evidence of black residents being blocked from moving to the suburbs by private threats and discrimination (Trudeau, 2006).

Less is known about school and workplace segregation than about residential segregation because relevant data must be obtained from administrative records and surveys rather than population-level censuses. Existing studies clearly show racial segregation in schools and workplaces, albeit at levels that are currently lower than those for residential segregation (Orfield, 2001; Tomaskovic-Devey et al., 2006). Historical trends and links with residence, however, are complicated. In the early 20th century, Southern cities tended to be less residentially segregated than Northern ones, but they also had a broad set of laws mandating complete segregation in schools, many workplaces, and other areas of life (Woodward, 2002; Orfield, 2001), something the North did not have—at least not at nearly the same scale. In both regions, the trend for schools has been initial decreases in segregation followed by increases (Orfield, 2001), while for workplaces it has been initial decreases followed by stasis (Tomaskovic-Devey et al., 2006).

The desegregation of Southern schools was a major focus of the civil rights litigation that resulted in *Brown v. Board of Education* and, later, in the wave of court mandated desegregation that reached a peak and produced significant integration in the late 1960s and early 1970s (Orfield, 2001). These efforts were attacked by the Nixon and Reagan administrations, however, and by the 1990s the Supreme Court had backed away from involvement in desegregation,[7] the lower courts were ending desegregation orders, and school segregation was again on the rise, albeit no longer driven by facially discriminatory laws (Orfield, 2001; Chemerinsky, 2002).

The North was by no means free of *de jure* segregation. Indeed, the Jim Crow system that the Southern states put in place at the turn of the 20th century (following a short period of relative integration) had been implemented first in the North (Woodward,

[6]See Comer v. Cisneros, 37 F.3d 775 (2d Cir. 1994).
[7]Bd. of Ed. v. Dowell, 498 U.S. 237 (1991).

2002). Explicit government-mandated school segregation existed in some Northern states during the early 20th century (Chemerinsky, 2002; Sugrue, 2008), and less explicit policies amounting to *de jure* segregation continued to be implemented in Northern school districts much later.[8] Nonetheless, 20th century school and workplace segregation in the North was more frequently accomplished through residential segregation and private discrimination, mechanisms that also became the driving forces in the South after the end of Jim Crow there (Kain, 1968).

The link between residential segregation and school or workplace segregation, of course, depends on school admission policy, job location, and a variety of issues related to mobility. The link for workplaces is related to the spatial mismatch hypothesis, which explains unemployment based on the mismatch between suburban job locations and segregated central city places of residence (Kain, 1968). Here the Wiggins case again provides an illustration. Wiggins' job at the mall was as a cashier, and the fact that she needed to travel from the city to the suburbs to find this type of work fits a general pattern of blue collar jobs moving out of central cities since the mid 20th century (Wilson, 1996, 1987; Kain, 1968). Moreover, the fact that her commute took 50 minutes reflects the lack of transportation options that the residents of poor neighborhoods face in many cities, the result of policies favoring private automobiles over public transportation systems despite the increasingly prohibitive costs of cars and fuel for many residents (Fisher, 2011; Wilson, 1996). Indeed, many of Wiggins' neighbors were unemployed while Buffalo-area jobs were going unfilled because they were simply inaccessible to them (Barnes & Blackman, 1996). Finally, the mall owners' refusal to allow city busses to stop on its premises and the city's unwillingness to force the issue let alone build a sidewalk or crosswalk servicing the highway bus stop are typical of the types of private and governmental actions that have frequently been taken throughout the United States to keep minorities, and particularly blacks, from accessing white neighborhoods (Barnes & Blackman, 1996). Around the time of Wiggins' death, black Buffalo

[8]See, e.g., Keyes v. School Dist. No. 1, 413 U.S. 189 (1973); United States v. School Dist. of Ferndale, 616 F.2d 895 (6th Cir. 1980).

residents were also complaining of being placed under police and private security surveillance when visiting the white suburbs, tactics that have been employed in many other communities as well (Trudeau, 2006; Barnes & Blackman, 1996).

Workplace segregation in the United States is also organized by gender, driven in part by employer discrimination. Overall, workplace gender segregation, measured at the establishment level, has dropped steadily since passage of the Civil Rights Act of 1964, although it still clearly exists (Tomaskovic-Devey et al., 2006). There is also an interesting interaction between race and gender that suggests the role of differential time constraints: In a comparison of tract-level residential and workplace segregation in Los Angeles, Ellis et al. (2004) found that racial segregation was lower at work than at home, but that the difference was smaller for women than for men. One explanation is that women remain more racially segregated because of time constraints that keep them closer to their (segregated) homes.

Examining segregation at home, school, and work in this manner helps in imagining what patterns of activity-space segregation may look like if we would measure them comprehensively. For example, the study by Ellis et al. (2004) suggests how segregation changes over the course of the day. Even this study does not have real timing information (instead assuming that everyone is at home and at work at approximately the same time), and it does not include information about the places in which people spend time apart from home and work. Nonetheless, studying segregation in different types of socially significant places like these helps bring to light many of the continuing causes of segregation. It is partly these causes that motivate the study of activity-space segregation, as they suggest possibilities for diminishing it or alleviating its most harmful consequences. The consequences, of course, are the primary motivation and it is to these that we now turn.

2.2 Consequences

For Cynthia Wiggins, the consequences of Buffalo segregation center on the environment to which she was exposed—namely, the difficulties of living in a neighborhood with limited jobs and public transportation options and the hazards of a seven-lane highway lacking sidewalks or a crosswalk. These are only the details that we know, but they illustrate the basic importance of place in driving the social consequences that flow from activity-space segregation.

As the residential segregation literature has demonstrated, the uneven distribution of resources across space means that access to these resources will depend on the spatial distribution of people (Fischer & Tienda, 2006; Massey, 1996). In the case of activity-space segregation, the temporal dimension must also be taken into account. The resources to which one has access in a business district, for instance, are very different at noon than at midnight. Access to these resources may also depend on a variety of socio-economic factors, but to the extent that we seek to understand how access is limited by space beyond simply place of residence, we must look also at time. Resources come to be unevenly distributed across space and time for a variety of reasons. One important one is the uneven distribution of people, which can distort the political process in ways that reinforce and exacerbate inequality (Massey, 1996).

The resources at issue are broad. Everything from the jobs, transportation networks, sidewalks, and crosswalks Wiggins was lacking, to health care providers, schools, child care, fire and police services, parks and cultural institutions, grocery stores and other private markets, and clean air and water. We can also think of the distribution of harmful or unpleasant factors like environmental pollutants, noise, or traffic.

In addition, to consequences that depend on place, activity-space segregation also operates through contact with people. It is through this contact that ideas, information, and culture are transmitted, affecting not just economic and social capital but also the values, aspirations, and reference groups that drive and shape human action (Raijman & Tienda, 2000b, 2000a; Massey, 1996; Massey & Denton, 1993; Wilson, 1987). Proximity to others affects prejudice, intergroup conflict, political views, and the possibilities for collective action as well as access to social networks, friendship, and romance. It also determines exposure to crime, disease, and other social ills (Massey, 2001, 1996). Most of these consequences depend on the social quality of the interaction that occurs, not merely spatio-temporal proximity. For instance, the proximity between a waiter and a diner in a restaurant has different social consequences than that between co-workers sharing an office. Even within the workplace, differences in power and life experiences, both often structured along lines of race and gender, are likely to shape the social consequences of proximity quite strongly. Indeed, black and white or male and female co-workers may form very different perceptions of the same events taking place in their shared office—particularly when it comes to questions of discrimination and sexual harassment (Robinson, 2008).

In addition to consequences that flow from contact with places and with people, the consequences of activity-space segregation also flow from the quality of movement itself. A long commute to and from work, like the one Cynthia Wiggins faced, influences both work and leisure. Whether people commute by car or foot has health affects based on exercise and hazards (as shown in very stark terms in Wiggins' case), and it does so independently of the places with which they come into contact during this commute. Finally, movement can affect not just the people moving, but also those around them. There may be large differences in quality of life and safety between a neighborhood filled with people passing through and one filled with people who have social ties.

3 Measuring activity-space segregation

Given this list of potential social consequences, activity-space segregation should be measured in terms of contact with people and places, as well as movement itself. People and places are also the terms on which residential segregation is defined and it is sensible to draw on existing approaches to residential segregation because these are the product of years of theoretical and empirical investigation and already familiar to researchers across the social sciences. The residential segregation indexes provide two-dimensional starting points on which to build three- and four-dimensional indexes of activity-space segregation. After making the basic conversion from residential to activity-space segregation, we can then make further refinements to take into account issues that are particular to activity-space, including movement.

3.1 Two-dimensional starting point: Segregation on a Cartesian plane

Standard indexes of residential segregation view the city as a Cartesian plane, divided into areal units that are generally taken, for convenience, from the units in which census data are provided: tracts, block-groups, or blocks. The basic measurements that go into each index are the number of residents in each unit, disaggregated by race, ethnicity, or some other characteristic of interest. For purposes of discussion, consider a city composed of black and white residents and divided into census tract areal units. Massey and Denton (1988) identify 20 distinct indexes that may be used to measure residential segregation, which they organize within five categories: centralization, concentration, evenness, exposure, and clustering. I will discuss each of these categories except for centralization, which I leave out because its relevance is tied specifically to residence and so there appears little to be gained from expanding it into activity space.[9]

Concentration is a measure of how people are distributed relative to places, with the places generally defined as areal units. The smaller the space into which people are squeezed, the more concentrated they are. The most common index of concentration is the delta index (Massey & Denton, 1988), defined as:

[9] Centralization is a measure of the distribution of residences relative to the city center, a question of particular relevance to theories of urban growth and immigrant assimilation (e.g., Burgess, 1928).

$$\text{DEL} = \frac{1}{2}\sum_{i=1}^{n}\left|\frac{x_i}{X} - \frac{a_i}{A}\right| \tag{3.1}$$

where x_i is the number of black residents in our hypothetical city in areal unit i, X is the total number of black residents in the city, a_i is the land area of unit i, and A is the total land area of the city. The delta index measures how evenly people's places of residence are distributed across areal units, taking into account the units' land areas, and it ranges from 0 (perfectly even) to 1 (perfectly uneven). It can be interpreted, in our scenario, as the proportion of the city's total black population that would have to change areal units in order to achieve a perfectly even distribution across space (assuming people are distributed evenly within each areal unit).

Of course, no actual city is constructed in a way to allow for a perfectly even distribution of residents across space, as this would require a perfectly even distribution of dwellings. More information about concentration—relative to the distribution of dwellings—can be obtained from the absolute concentration (ACO) and relative concentration (RCO) indexes proposed by Massey and Denton (1988). These are defined as:

$$\text{ACO} = 1 - \left(\sum_{i=1}^{n}(\frac{x_i a_i}{X}) - \sum_{i=1}^{n_1}(\frac{t_i a_i}{T_1})\right) / \left(\sum_{i=n_2}^{n}(\frac{t_i a_i}{T_1}) - \sum_{i=1}^{n_1}(\frac{t_i a_i}{T_1})\right) \tag{3.2}$$

$$\text{RCO} = \left(\frac{\sum_{i=1}^{n}(\frac{x_i a_i}{X})}{\sum_{i=1}^{n}(\frac{y_i a_i}{Y})} - 1\right) / \left(\frac{\sum_{i=1}^{n_1}(\frac{t_i a_i}{T})}{\sum_{i=n_2}^{n}(\frac{t_i a_i}{T_2})} - 1\right) \tag{3.3}$$

where areal units are ordered by land area from smallest to largest, a_i, x_i and X are defined as above, y_i and Y are, respectively, the white population in areal unit i and that in the overall city, t_i is the total residential population in areal unit i, n_1 is the rank of the tract where the cumulative total population of areal units from 1 to n_1 is equal to the city's total black population, n_2 is the rank of the tract where the cumulative total population of areal units from n to n_2 is equal to the city's total black population, T_1 is the cumulative total population of tracts 1 through n_1, and T_2 is the cumulative total population of tracts n_2

through n.

These indexes incorporate information about dwellings by relying on the assumption that the number of dwelling places in each areal unit is fixed, and is equal to the total residential population of the unit. Given this assumption, the absolute concentration index compares the average land area of the areal units inhabited by black members ($\sum_{i=1}^{n}(x_i a_i/X)$) with the minimum and maximum possible averages—the minimum being the average if black members lived in the smallest areal units ($\sum_{i=1}^{n_1}(t_i a_i/T_1)$), and the maximum being that if black members lived in the largest areal units ($\sum_{i=n_2}^{n}(t_i a_i/T_2)$). The relative concentration index takes the ratio of the average land area of the areal units inhabited by black members to that inhabited by white members, and compares this to the ratio that would exist if black members lived in the smallest areal units and white members lived in the largest.

The comparison scenarios in each index essentially take all residents out of their dwellings, and place the members of one group into dwelling places, areal unit by areal unit, starting either with the smallest unit and working up or with the largest unit and working down. This means that the minimum concentration scenario is neither an even distribution in space (as it is in the delta index) nor the minimum possible concentration in space. Instead, it is simply the distribution that places residents in the largest possible areal units. (Lower concentrations are possible in many cases by distributing residents into more areal units, even if they are not the largest ones.) Moreover, the assumption that the number of dwelling places in each areal unit is fixed according to total population is of questionable validity, and it becomes clearly problematic when we try to shift from residential segregation to activity-space segregation.

Although the factor analysis of U.S. census data carried out by Massey and Denton (1988) suggested that the absolute and relative concentration indexes captured more unique information about the concentration dimension than did the delta index, an analysis of subsequent census data by Massey, White, and Phua (1996) suggested the opposite. One reason for the latter finding could be that the absolute and relative concentration indexes address not only the question of how people are distributed relative to space, but also the question of how they are distributed relative to each other. This means that these indexes overlap, to some extent, with the measures of unevenness, exposure, and clustering discussed below.

Unevenness shifts the focus from places to people. The indexes in this category measure how one group is distributed relative to the distribution of another group. A city is perfectly even when each areal unit contains the same proportion of each group as in the city as a whole, and it is perfectly uneven when the groups share no areal units in common.

The most common measure of unevenness is the dissimilarity index (D), defined as:

$$D = \sum_{i=1}^{n} \frac{t_i|p_i - P|}{2TP(1-P)} \tag{3.4}$$

where t_i is the total population of blacks and whites in areal unit i, p_i is the proportion of that population composed of blacks, T is the total population of blacks and whites in the city and P is the proportion of that population composed of blacks. An equivalent expression of the dissimilarity index is:

$$D = \frac{1}{2} \sum_{i=1}^{n} \left| \frac{x_i}{X} - \frac{y_i}{Y} \right| \tag{3.5}$$

where x_i and y_i are, respectively, the number of black and white members residing in areal unit i, and X and Y are, respectively, the total number of black and white members residing in the city. As can be seen clearly from this latter expression, the dissimilarity index takes the same general form as the delta index, and simply substitutes the distribution of white members in place of the distribution of areal unit sizes. Thus, the dissimilarity index also ranges between 0 and 1 and it represents the proportion of the black population that would need to move to a different areal unit in order to achieve a perfectly even distribution with respect to the white population's distribution.

Massey and Denton (1988) recommend using the dissimilarity index as the primary measure of unevenness because it is easy to calculate and interpret, it has long been used in the segregation literature, and it captures approximately the same amount of unique information as competing choices when tested empirically. They note, however, that it has some drawbacks, including being highly sensitive to random noise in cities with few minority members relative to areal units, and being entirely insensitive to transfers of group members among areal units in which they are already overrepresented or among those in which they are already underrepresented.[10]

Like unevenness, **exposure** also focuses on people. With exposure, however, the emphasis is less on the distribution of people than on the chances for inter- and intra-group contact that this distribution produces (Massey & Denton, 1988). One measure of exposure is the interaction index (${}_xP^*_y$), which measures the mean areal unit proportion of white members experienced by black members. Another is the isolation index (${}_xP^*_x$), which measures the mean areal unit proportion of black members experienced by black members. The indexes are expressed, respectively, as:

$$ {}_xP^*_y = \sum_{i=1}^{n} \left(\frac{x_i}{X}\right)\left(\frac{y_i}{t_i}\right) \tag{3.7} $$

$$ {}_xP^*_x = \sum_{i=1}^{n} \left(\frac{x_i}{X}\right)\left(\frac{x_i}{t_i}\right) \tag{3.8} $$

where all variables are defined as above.

[10] An alternative to the dissimilarity index that does not suffer from these flaws is the Gini index (G), defined as:

$$ G = \sum_{i=1}^{n}\sum_{j=1}^{n} \frac{t_i t_j |p_i - p_j|}{2T^2 P(1-P)} \tag{3.6} $$

Other alternatives include the Atkinson Index, $A = 1 - \frac{P}{1-P}\left(\sum_{i=1}^{n} \frac{(1-P)^{1-b} p_i^b t_i}{PT}\right)^{1/(1-b)}$ with b introduced as a parameter chosen by the researcher to determine how much weight to give areal units in which minority members are overrepresented relative to those in which they are underrepresented, and the entropy index, defined as $H = \sum_{i=1}^{n} \frac{t_i(E-E_i)}{ET}$, where $E = (P)log[1/P] + (1-P)log[1/(1-P)]$ and $E_i = (p_i)log[1/p_i] + (1-p_i)log[1/(1-p_i)]$ and T, P, and p_i are defined as before.

The final category of residential segregation indexes, **clustering**, looks beyond the composition of areal units and asks instead how the units themselves are arranged. The more units in which one group is overrepresented are contiguous with each other, the more highly clustered the group is considered to be. There are a number of different indexes of clustering. The empirical analysis in Massey and Denton (1988) suggests that the one best suited for capturing unique information is White's (1983) index of spatial proximity (SP), while the analysis in Massey et al. (1996) suggests the best is the relative clustering index (RCL). These two alternatives are defined, respectively, as:

$$\mathrm{SP} = \frac{XP_{xx} + YP_{yy}}{TP_{tt}} \tag{3.9}$$

$$\mathrm{RCL} = \frac{P_{xx}}{P_{yy}} - 1 \tag{3.10}$$

Both indexes rely on P_{xx} (and by analogy, P_{yy} and P_{tt}), a measure of mean proximity that White (1983) defined as:

$$\mathrm{P}_{xx} = \sum_{i=1}^{n}\sum_{j=1}^{n} \frac{x_i x_j f(d_{ij})}{X^2} \tag{3.11}$$

where d_{ij} is the geographic distance between the areal units inhabited by individuals i and j (with distances between individuals in the same areal unit approximated as a function of the unit's area), and $f(d_{ij})$ is a function intended to capture the relationship between distance and social interaction. White (1983) tested his spatial proximity index with a number of different functions in this role, suggesting $e^{-d_{ij}}$ as a preliminary best in the absence of some guiding theory of interaction, and $e^{-d_{ij}}$ is what Massey and Denton (1988) and Massey et al. (1996) used in their analysis.

The SP index gives the average of the intra-group proximities weighted by the fraction of each group in the population (White, 1983), whereas the RCL index gives the average proximity between members of one group relative to that between members of the other

(1988).

3.2 Collecting Movement Data

Shifting from residential segregation to activity-space segregation requires, first of all, human movement data. There are two basic approaches to studying human movement (or the movement of any group of objects) at the scale in which we are interested here: the Eulerian approach, which involves picking points in space and recording the people who move past these points, and the Lagrangian approach, which involves picking people and recording the space through which they move (Ōkubo & Levin, 2001). Censuses are a type of Eulerian approach, whereas time-use surveys are a type of Lagrangian approach. The latter are better suited for studying activity-space segregation, and even very basic time-use surveys can provide important segregation information. There are limits, however, to what can be learned from self-reported movement data, given faulty perception and memory, and the logistical problems of implementation on a large scale (Stopher, FitzGerald, & Xu, 2007; Murakami & Wagner, 1999; Golob & Meurs, 1986).

An alternative to self-reported movement data is to attach to each individual a device that automatically measures and records the individual's location or transmits signals to an external receiver that does so. Until recently, this was an expensive proposition that could be done only on a relatively small scale. The rapid and widespread adoption of mobile phones by people around the world has changed all of this. The simplest of these devices leave traces of their locations every time they transmit signals to a cell tower, and the more sophisticated ones can determine their own locations based on signals received from cell towers, satellites, and other sources. A growing body of research shows the variety of ways in which mobile phones may be used to study human movement and the quality of the data they are able to produce (Palmer et al., in press; Ahas, 2011; Ahas & Mark, 2005; Asakura & Hato, 2004).

At the same time, mobile phone data are also limited in important ways. First, this type of spatial data raises serious privacy concerns. Precise location tracking requires not only the consent of each individual subject who volunteers to be part of a study,[11] but also safeguards to protect confidential information (Palmer et al., in press). Second, there is generally a trade-off, even in mobile phone studies, between the quality and quantity of data, with the largest-N studies lacking any demographic information about participants (Isaacman et al., 2010; Wesolowski & Eagle, 2010), and the studies with the most detail being limited in scale (Pentland, 2007).

3.3 Segregation in space-time

Measuring activity-space segregation requires that time be added to the Cartesian axes on which residential segregation measures rely. Instead of simply counting residents as points falling within two-dimensional areal units, any measure of activity-space segregation must contend with the paths individuals trace through time while going about their daily routines.[12] This means thinking in three dimensions, or maybe even thinking in four.

The shift from residential segregation indexes also requires a reexamination of units of measure. Apart from the question of incorporating time into areal units, we must also consider whether the spatial component of the units used for measuring residence can capture the aspects of activity-space segregation in which we are interested. Alternatives include finding new rules by which to divide cities into areal units or dropping the units entirely and measuring distances between the actual locations of individuals. The following section discusses the case of retaining pre-existing, two-dimensional areal units and simply adding time. The subsequent section then adds refinements to that basic model.

[11] Some studies rely on anonymized call detail records obtained from mobile network providers without the individual consent of each user (apart from whatever consent users give to the providers as part of their contracts) (Isaacman et al., 2010; Wesolowski & Eagle, 2010), but the demographic information that may be obtained in these studies is limited.

[12] It is not that research on residential segregation is unconcerned with time. Time is relevant to questions of residential mobility and dynamic models of residential segregation like Schelling's (1971) famous agent-based simulation. For these questions, however, the relevant time is at the scale of months or years—the periods between changes of residence—whereas activity-space segregation is concerned with hours and days.

3.3.1 Basic indexes: Averaging and Person-Hours

In the basic model, we must first choose an outer temporal boundary that will combine with the outer spatial boundary to define the overall space-time community under study, and we must choose internal temporal divisions that will define the space-time units across which the indexes will be calculated. The obvious choice for an outer temporal boundary is the day, given people's natural circadian rhythms. The choice of inner temporal boundaries, much like the choice of inner spatial boundaries, is somewhat more arbitrary and will likely be driven by data availability and convenience. For now, let us pick an hourly division and assume that the spatial division is the census tract, giving us a city-day divided into tract-hours.

The next step is to populate these tract-hours with the space-time paths that run through them. Data on these paths will almost certainly be discrete, and likely very messy, with irregular gaps along each individual's path and many individuals missing, but for now assume that we have continuous and complete path data. The number of people assigned to each space-time unit will be the sum of the paths running through the units, weighted according to the proportion of the time slice for which the path remains in the unit. For example, if a person's path runs through a tract-hour, but only remains within it for the first half of the hour, then that tract-hour will be assigned a half of a person-hour.

Given this setup, there are two straightforward methods to turn the residential segregation indexes into activity-space segregation indexes: (1) calculating the indexes separately for each hour and then averaging the results for the full day, and (2) calculating person-hour segregation across all space-time units. The averaging method is the most intuitive and easiest to implement. The indexes are calculated for each time slice exactly as is done for the residential segregation indexes, and the mean of all results is computed. If we represent each index defined above, calculated for time i, as Λ_i, then the average activity-space segregation index $\overline{\Lambda}$ can be expressed as:

$$\overline{\Lambda} = \frac{1}{m} \sum_{i=1}^{m} \Lambda_i \tag{3.12}$$

where m is the number of time units into which the space-time object has been divided. Results are interpreted simply as average scores. Thus, the black-white dissimilarity index calculated for our hypothetical city-day will represent the average proportion of black inhabitants who would need to change tracts each hour to yield a perfectly even distribution of blacks relative to whites. The black-white interaction index will yield the average hourly proportion of whites in the tract in which the average black inhabitant spends time during the day. The delta index of concentration will yield the average proportion of black inhabitants who would need to change tracts each hour to yield a perfectly even distribution of blacks relative to tract land areas. The the spatial proximity index of clustering will yield the average of the hourly weighted average black and white intra-group proximity.

The second method is to actually calculate the indexes over the full city-day. Here, the results will be interpreted in terms of person-hours: The question will no longer be one of how people are distributed relative to places or to other people, but how person-hours are distributed relative to place-hours or other person-hours. This will become clearer by examining each index individually.

For **concentration**, Massey and Denton (1988) recommends the absolute concentration index, while Massey et al. (1996) recommends the delta index. Activity-space concentration should be better captured using the delta index than the absolute concentration index because the latter's assumption of fixed populations becomes unrealistic when applied to moving people as opposed to residences. Moreover, the delta index does better than the others in the empirical tests performed by Massey et al. (1996) and it is simpler to compute and interpret. The averaging method for activity-space concentration, using the delta index, can be expressed as:

$$\overline{\text{DEL}} = \frac{1}{m}\sum_{i=1}^{m}\text{DEL}_i = \frac{1}{m}\sum_{i=1}^{m}\frac{1}{2}\sum_{j=1}^{n}\left|\frac{x_{ij}}{X_i} - \frac{a_j}{A}\right| \tag{3.13}$$

where x_{ij} is the number of black members present in tract j during time i, a_j is the land area of tract j, X_i is the total number of blacks present in the city during time i and A is the total land area of the city. This measures the average proportion of black members who would need to change tracts each time slice to yield a perfectly even distribution of black members relative to tract land areas.

The person-hours approach can be expressed as:

$$\text{DEL}' = \frac{1}{2}\sum_{i=1}^{m}\sum_{j=1}^{n}\left|\frac{x_{ij}}{\sum_{k=1}^{m} X_k} - \frac{a_j}{mA}\right| \tag{3.14}$$

This approach yields the proportion of black person-hours that would have to be moved—either to different tracts or to different times of day—in order to achieve a perfectly even distribution of black person-hours relative to space across the full city-day. Two things should be noted about this. First, if the number of black members in the city remains constant throughout the full day, then the averaging approach and the person-hours approach will produce identical results. (I offer a simple proof of this in Appendix A.) Second, the possibility of moving a person-hour along the time axis, as opposed to the space axis, may be troubling in that it implies that the same person could end up in two locations at exactly the same time. Because the index points to moves that achieve evenness, however, this would happen only if people have entered or exited the city during the day, and the effect would be to move person-hours from times of above-average population to times of below-average population.

The averaging method for activity-space unevenness, using the dissimilarity index, can be expressed as:

$$\overline{\text{D}} = \frac{1}{m}\sum_{i=1}^{m}\frac{1}{2}\sum_{j=1}^{n}\left|\frac{x_{ij}}{X_i} - \frac{y_{ij}}{Y_i}\right| \tag{3.15}$$

where x_{ij} and y_{ij} are, respectively, the number of black and white members present in tract j during time i, and X_i and Y_i are, respectively, the total number of black and white members present in the city during time i. This measures the average proportion of black members who would need to change tracts at each time slice to yield a perfectly even spatial distribution of black members relative to white members.

The person-hours approach to the dissimilarity index can be expressed as:

$$\mathrm{D}' = \frac{1}{2} \sum_{i=1}^{m} \sum_{j=1}^{n} \left| \frac{x_{ij}}{\sum_{k=1}^{m} X_k} - \frac{y_{ij}}{\sum_{k=1}^{m} Y_k} \right| \tag{3.16}$$

This approach yields the proportion of black person-hours that would have to be moved—either to different tracts or to different times of day—in order to achieve a perfectly even distribution of black person-hours relative to white person-hours across the full city-day. In this case, the number of black members and white members in the city must both remain constant throughout the full day for the averaging approach and the person-hours approach to produce identical results (Appendix A), and the same issue, noted above, of moving person-hours along the time axis pertains here as well.

The averaging method for activity-space **exposure**, using the interaction index, can be expressed as:

$$\overline{{}_x\mathrm{P}^*_y} = \frac{1}{m} \sum_{i=1}^{m} {}_x\mathrm{P}^*_{yi} = \frac{1}{m} \sum_{i=1}^{m} \sum_{j=1}^{n} \left(\frac{x_{ij}}{X_i} \cdot \frac{y_{ij}}{t_{ij}} \right) \tag{3.17}$$

where x_{ij} and y_{ij} are, respectively, the number of black and white members present in tract j during hour i, X_i is the total number of black members present in the city during hour i, and t_{ij} is the total number of black and white members present in tract j during hour i. This measures the average mean tract proportion of white members experienced by black members over the course of the day.

The person-hours approach to the interaction index can be expressed as:

$$ {}_x\mathrm{P}_y^{*'} = \sum_{i=1}^{m} \sum_{j=1}^{n} \left(\frac{x_{ij}}{\sum_{k=1}^{m} X_k} \cdot \frac{y_{ij}}{t_{ij}} \right) \tag{3.18} $$

This approach yields the mean tract proportion of white person-hours experienced by black person-hours. If the total number of black members remains constant throughout the day, the averaging approach and the person-hours approach give identical results (Appendix A). (The issue of moving person-hours along the time axes does not pertain here.)

The averaging method for activity-space **clustering**, using the spatial proximity index, can be expressed as:

$$ \overline{\mathrm{SP}} = \frac{1}{m} \sum_{i=1}^{m} \mathrm{SP}_i = \frac{1}{m} \sum_{i=1}^{m} \frac{XP_{xx_i} + YP_{yy_i}}{TP_{tt_i}} \tag{3.19} $$

with the proximity measure, P_{xx_i} (and, by analogy, P_{yy_i} and P_{tt_i}) defined here as:

$$ \mathrm{P}_{xx_i} = \sum_{j=1}^{n} \sum_{k=1}^{n} \frac{x_{ij} x_{ik} f(d_{ijk})}{X_i^2} \tag{3.20} $$

where d_{ijk} is the geographic distance between the centroids of areal units j and k at time i, and d_{ijj} is approximated based on the areal unit area. Following White (1983) and Massey and Denton (1988), the distance function $f(d_{ijk})$ applied here will be $e^{-d_{ijk}}$, although other functions may be used.

The person-hours approach to the spatial proximity index can be expressed as:

$$ \mathrm{SP}' = \frac{\left(\sum_{k=1}^{m} X_k\right) P'_{xx} + \left(\sum_{k=1}^{m} Y_k\right) P'_{yy}}{\left(\sum_{k=1}^{m} T_k\right) P'_{tt}}, \tag{3.21} $$

with P'_{xx} (and, by anology, P'_{yy} and P'_{tt}) now defined as:

$$ \mathrm{P}'_{xx} = \sum_{i=1}^{m \cdot n} \sum_{j=1}^{m \cdot n} \frac{x_i x_j f(d_{ij})}{\left(\sum_{k=1}^{m} X_k\right)^2} \tag{3.22} $$

where each of the $m \cdot n$ space-time units is now assigned a single index value, x_i and x_j are the number of black residents in space-time units i and j, and $f(d_{ij})$ is a function of the distance between these units. This index is slightly more complicated than the others because it requires some decision about how to measure distance in space and time simultaneously. One obvious approach is to retain White's (1983) exponential proximity function for the distance component and simply combine this with an indicator function, I_A that takes the value 1 when i and j are taken from contiguous time slices and 0 otherwise.

3.3.2 Refinements

One weakness of the residential segregation indexes and, by extension, the averaging and person-hour approaches to activity-space segregation, is their reliance on census tracts or blocks as areal units. Ideally, the areal units that go into an index would be based on some type of socially-relevant boundaries. For residential segregation, we have a concept of neighborhood as the relevant space, but it is not clear that census tracts or blocks do a good job of approximating this space. One problem is that the concept of neighborhood itself is a fuzzy one, and the term may mean different things for different purposes. Definitions of neighborhood usually emphasize a spatial element (e.g., neighborhood as a "spatial construction denoting a geographical unit in which residents share proximity") and an element of social interaction and solidarity, but specifics vary as do views on the historical evolution of neighborhoods as meaningful divisions within American cities (Chaskin, 1997).

Grannis (1998) proposes that neighborhoods may be better defined by networks of small, residential streets, known as tertiary streets, because these are the streets along which neighborly relations typically take place. Specifically, he defines t-communities as collections of houses that are mutually reachable by travelling only on tertiary streets, without having to cross larger ones, and he examines racial variation among groups of t-communities that are also connected by tertiary streets. He finds that residential racial composition is better predicted by tertiary street connections than by simple spatial relations, even over long distances Grannis (1998), and that t-communities tend to be racially homogeneous internally, with racial variation occurring instead between them (Grannis, 2005).

This suggests that using t-communities as areal units could be an improvement over using census tracts. For activity-space segregation, however, there is the added problem of what neighborhood means outside of the residential context. Indeed, the very concept of neighborhood is generally linked to residence (Chaskin, 1997). It may be that the boundaries of socially-relevant space change throughout the day or depending on activity. From that perspective, we may be better off moving away from areal units altogether and measuring distances between individual people. One of the advantages of using mobile phone data is that it makes this possible by including precise locations (in contrast to the aggregated census data used for residential segregation).

One way to do this is to construct an index of **individual proximity**, defined as:

$$\mathrm{IP} = \frac{XP_{xx} + YP_{yy}}{TP_{tt}} \tag{3.23}$$

where $\mathrm{P}_{xx} = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{n} \frac{f(d_{ijk})}{m(n^2-n)}$, $f(d_{ijk}) = e^{-d_{ijk}}$, $\forall\, j \neq k$, and d_{ijk} is the geographic distance, along the spatial axes, between individuals j and k at time i. This index is an extension of White's (1983) spatial proximity index, substituting distances between each individual for distances between each areal unit and averaging over time units. In fact, White's original formulation of the index started with the concept of individual distances and substituted areal unit distances due to problems of data collection when dealing with residential census populations. Precise movement data may make it possible to return to the original concept, albeit with only small samples of the population. As in the spatial proximity index, the distance within which individuals are considered proximate to one another is controlled by the function $f(d_{ijk})$, which may be modified depending on the situation and which will affect the type of spatial relationship that the index captures. Once unlinked from areal units, this index appears to lie somewhere in between a measure of unevenness and one of clustering.

Another individual distance approach is to construct an index of **personal-space exposure**, defined as:

$$ {}_{x}\mathrm{PS}_{y}^{*} = \sum_{i=1}^{n} \frac{q_i}{n} \tag{3.24} $$

where q_i is the number of white person-hours that fall within individual i's "personal interaction space," defined as a cylinder (or sphere) with radius r along the spatial axes and height h along the time axis.

An important advantage of these individual distance approaches is that they allow altitude to be incorporated into the indexes. Although altitude might seem like a strange concern, any index constructed in a city with tall buildings will need to confront it. People who overlap in two-dimensional space may be on different floors of the same building and never come into contact. Moreover, the environments to which they are exposed on their different floors may also be very different. Just consider the situation of a CEO in a skyscraper's top-floor office compared to the doorman working in the lobby or the janitor working in the basement.

The two individual distance approaches to the neighborhood problem both address the interaction element of the neighborhood definition. To address the space element, we could look instead to measures of **habitat use** drawn from ecology. The insight here is that if care about neighborhoods because of what they tell us about the spaces likely to be visited, we could just as well examine the actual spaces occupied. Moreover, we could group spaces based on some characteristic of interest (e.g., air quality, property value, crime rate) and calculate, for each group, the average proportion of the day spent in each habitat type.

So far, we have not addressed the question of movement, which is not captured by any of the existing residential segregation indexes. Here again, we can draw on the ecology literature and use **minimum convex polygons** or **maximum distances** to measure the extent of the space through which people move on a daily basis. The minimum convex

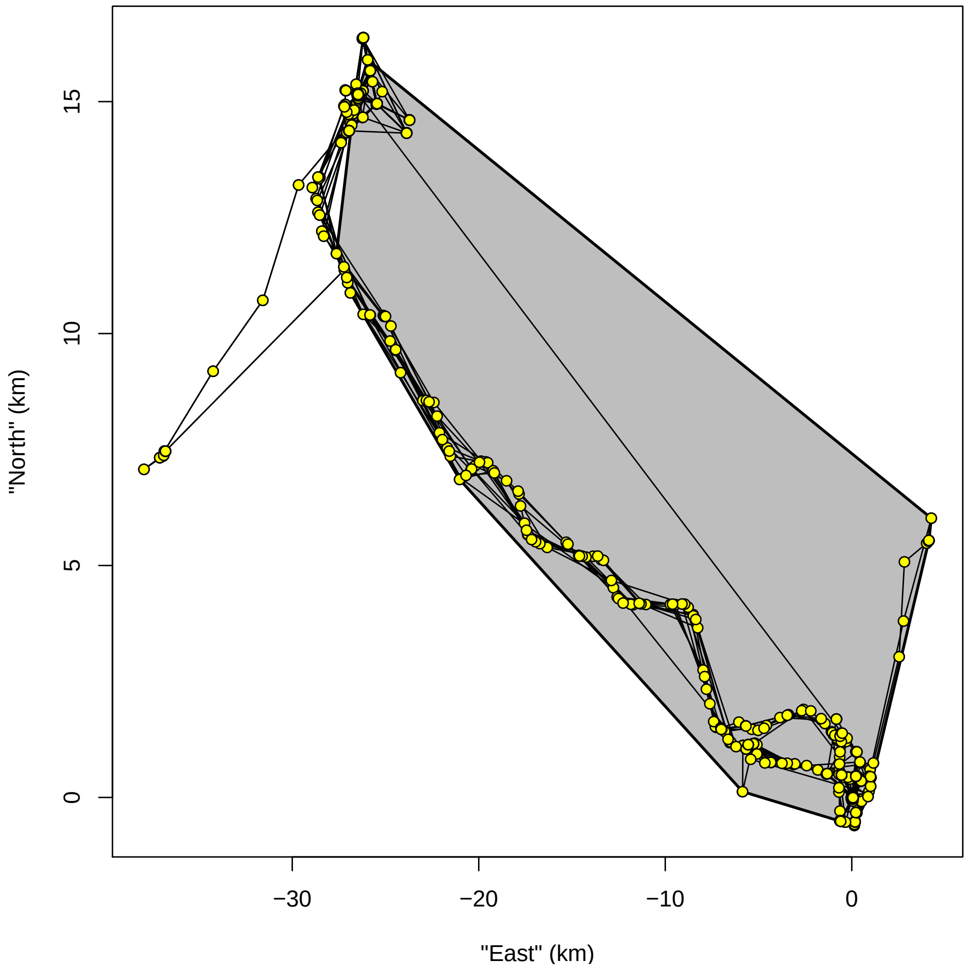

Figure 6 – 95% Minimum convex polygon drawn around 95% of the location estimates for one user observed over 11.5 days of observation in the Human Mobility Project Pilot Study (Palmer et al., in press).

polygon is simply the area of the smallest convex polygon that can be drawn around all or some fraction of a person's locations (Burgman & Fox, 2003) (see Figure 6). The maximum distance is the distance between the two location estimates for the given day that are farthest apart (Isaacman et al., 2010). In both cases, groups would be compared based on the mean and distribution of these areas.[13]

[13]Although the minimum convex polygon is very commonly used for so-called home-range analysis in ecology, one drawback is that it is biased by sampling error and shape of the space utilized (Burgman & Fox, 2003).

4 Demonstration with simulated data

To demonstrate the proposed indexes, I have applied them to data generated from a large computer simulation of human movement set in Buffalo, New York. I started the simulation started with the full 2000 census populations of non-Hispanic whites ($n = 151,488$) and non-Hispanic blacks ($n = 107,103$) in the City of Buffalo, placed randomly on streets within their census tracts of residence. Each simulated person "walked" along the Buffalo City and Erie County road network at 4 km per hour for 8 hours of simulation time. The walks were programmed to take the form of network-constrained, truncated Lévy flights: After choosing a random direction along the road, each person then chose a random distance drawn from a truncated power law distribution. The minimum and maximum of this distribution were set to 100 m and 100 km, and after each flight a new direction and distance were randomly drawn. Road and direction were also randomly selected at each intersection, and when people reached the end of a road or the county boundary they simply turned around and continued walking.

The simulation is obviously a far stretch from reality, but it provides a rich set of data with which activity-space indexes may be tested and demonstrated. It also serves as a baseline against which to compare empirical data and helps in tackling the question of how much activity-space segregation is influenced by place of residence. We expect people to be well mixed when moving along random paths, but this mixing may take some time when their starting points and ending points each day are highly segregated, as is the case in Buffalo. The simulation helps us to think about how quickly residentially-induced segregation might drop during the day if there were no additional factors causing segregation outside the home.

As a simple visualization of the changes in census tract composition that occurred during the simulation, Figure 7 shows an animation of the Buffalo City black-white tract ratios at each half-hour time slice. Buffalo's high level of residential segregation is immediately apparent in the first frame, with over four times as many blacks as whites in the

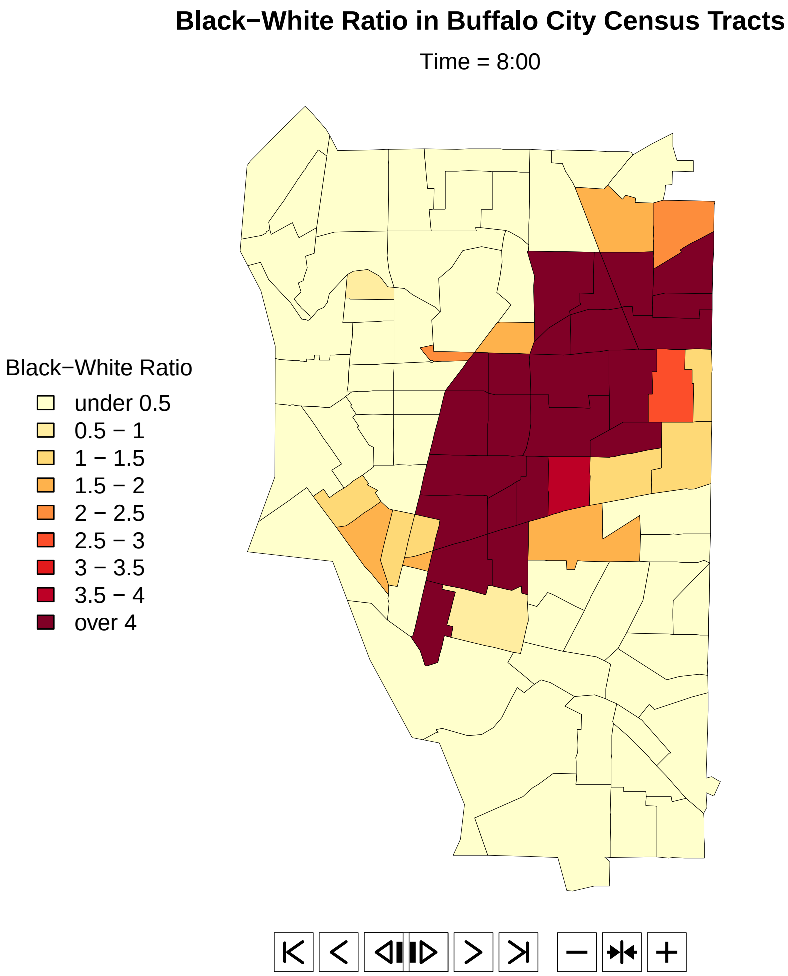

Figure 7 – Animation of black-white tract ratios at half-hour increments during 8 hours of truncated Lévy flights performed on the Buffalo City and Erie County road networks by the full 2000 census population of non-Hispanic whites and non-Hispanic blacks. (Click on the controls to cycle through the frames).

central census tracts, and less blacks then whites in the surrounding ones. As the simulation progresses, segregation clearly decreases, with no tracts containing more than four times as many blacks as whites by the end, but still notable differences in the composition of the central tracts and their surroundings. The simulation covers only 8 hours, but one can imagine these people following the same paths back to their homes, and consequently increasing the level of segregation back to the residential starting point by the end of the day.

Results of the basic activity-space segregation index calculations are shown in Figure 8. (Note that the scales of these plots differ so that as much detail from each one can be shown.) The averaging and person hours indexes are indicated with the red and green horizontal lines. For comparison, the corresponding traditional residential segregation indexes (calculated at time zero, when all simulated people are within their actual census tracts of residence) are indicated with the blue horizontal lines, and the traditional indexes calculated at each half-hour increment are indicated with the black curves. The averaging and person-hours approaches yield nearly identical results and in all cases the activity-space measures show lower segregation than the residential measures. (The two measures are not expected to be identical in this simulation because the simulated people were allowed to leave Buffalo City as long as they remained within Erie county.) More interestingly, moderate levels of segregation remain even after 8 hours of random mixing.

According to the activity-space extensions of the dissimilarity index, over the course of the 8-hour period on average 55% of blacks would have needed to move to different census tracts in order to achieve an even distribution relative to whites, and 45% of blacks would have needed to do so in order to achieve an even distribution relative to tracts. Similarly, 55% of black person hours would have needed to be moved to different space-time units in order to achieve an even distribution relative to white person-hours, and 44% would have needed to be moved in order to achieve an even distribution relative to tracts.

In addition, blacks were closer to other blacks and whites were closer to other whites throughout the simulation than they were to members of the other group, giving an average spatial proximity score of 1.25. Likewise, black person-hours were closer in time and space to other black person hours and white person-hours were closer in time and space to other white person hours than either of these were to person-hours of the other group. Finally, on average blacks were located in census tracts with contemporaneous populations that were 36% white and black person-hours were located in tracts with contemporaneous person-hour populations that were 36% white.

Figure 9 shows the individual proximity index and the personal exposure index. I calculated these indexes using simple random samples of 2000 individuals from the full census

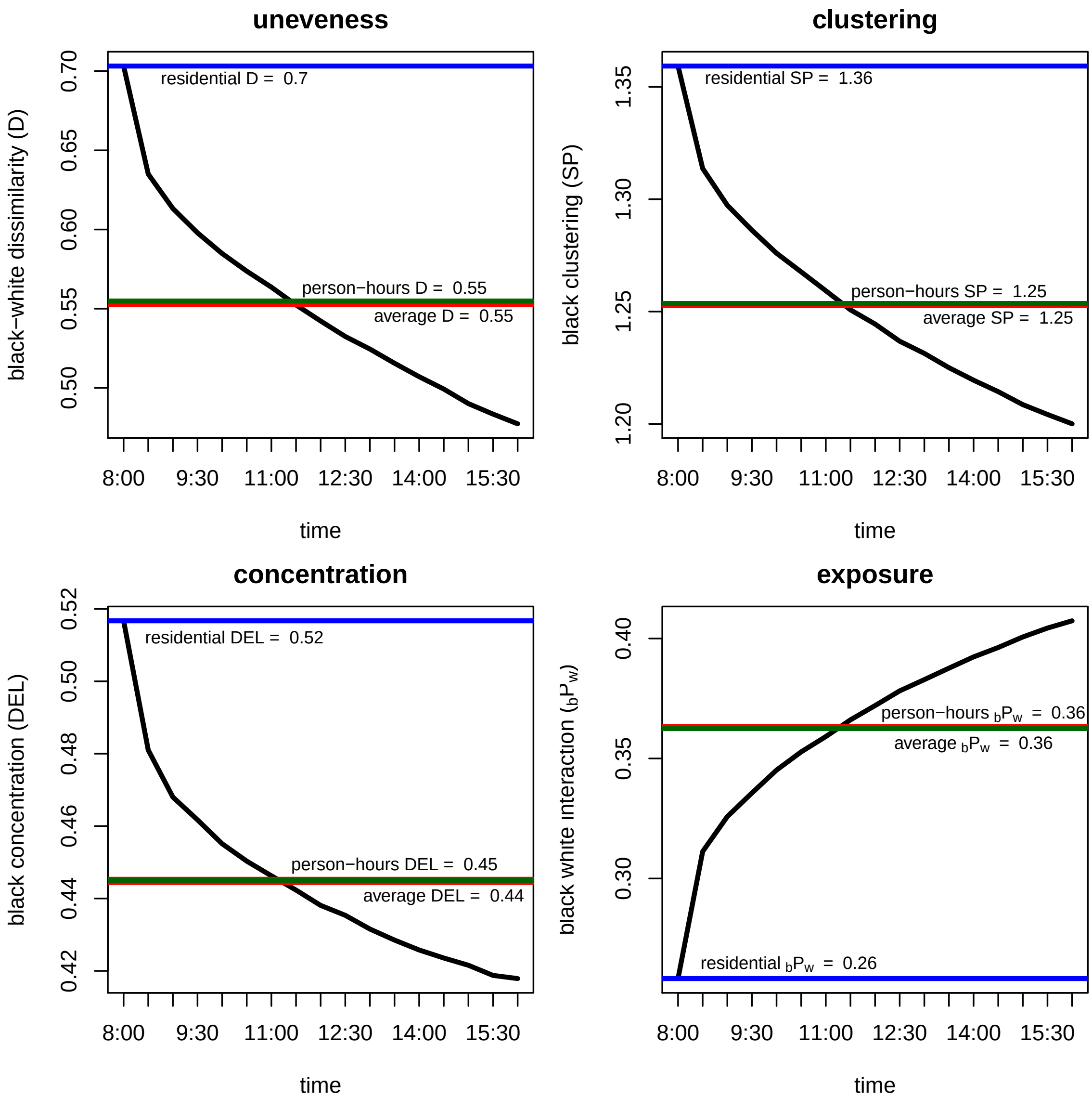

Figure 8 – Basic activity-space segregation indexes calculated from half-hour observations during 8 hours of truncated Lévy flights performed on the Buffalo City and Erie County road networks by the full 2000 census population of non-Hispanic whites and non-Hispanic blacks. Note that the scales of these plots differ from one another.

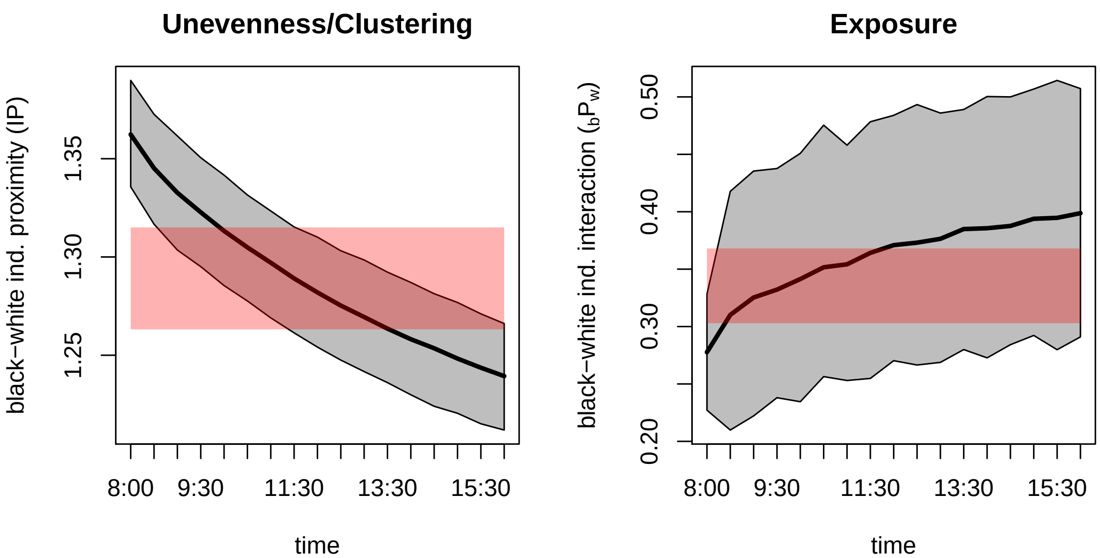

Figure 9 – Estimated individual proximity and personal exposure activity-space segregation indexes calculated from half-hour observations during 8 hours of truncated Lévy flights performed on the Buffalo City and Erie County road networks by sample of the 2000 census population of non-Hispanic whites and non-Hispanic blacks. Each index is calculated using 480 samples of 2000 individuals each and horizontal red band shows values within which 90% of the samples fall. Grey curve shows values for each half-hour time slice within which 90% of the samples fall, and black line is the mean of the sample values. Note that the scales of these plots differ from one another.

population because of the intensive computations required for the distance matrixes in these indexes, and because the data necessary for these indexes will never be full census data anyway. As an estimate of uncertainty, I calculated the indexes on each of 480 samples and plotted the values within which 90% of the results lie. The horizontal red bands in the figure indicate the results of the indexes calculated over the 8 hour period; the grey bands indicate results for each half-hour time slice and the black curve indicates the mean of these results.

These two individual-level measures of activity-space segregation correspond closely with the areal unit extensions of the traditional residential segregation measures. On one hand, this suggests that the individual level measures may not add much to what we can already learn from areal unit measures when full census data are available. However, it also suggests that the individual-level measures may be good substitutes for the areal unit measures when only limited data are available. In practice, activity-space segregation measures will almost always need to rely on limited data and so the individual-level measures may prove to be essential.

5 Conclusion

I started with the question of how to measure and understand systematic differences in the spaces people move through as they go about their daily activities. After considering what is already known about such systematic differences and their social significance, I have proposed the following seven approaches for measuring them:

- Averaging Approach
- Person-Hours Approach
- Individual Proximity
- Personal-Space Exposure
- Habitat Use
- Minimum Convex Polygons
- Maximum distances

The next steps in this research will be to test and evaluate each of these approaches using mobile phone location data and American Community Survey responses on places of residence and work. I plan to do this in two metropolitan areas in upstate New York: the large and highly segregated Buffalo-Niagara Falls Metropolitan Area, where Cynthia Wiggins lived, and the smaller and less segregated Utica-Rome Metropolitan area, for comparison. The ultimate goal, after evaluating and finalizing the measurement indexes, is to use them to compare cities throughout the United States with an eye to better understanding the ways in which segregation is driven by law and policy.

A Appendix

Equivalence between averaging and person-hours: DEL

$$\text{DEL}_i = \frac{1}{2}\sum_{j=1}^{n}\left|\frac{x_{ij}}{X_i} - \frac{a_j}{A}\right|$$

$$\overline{\mathrm{DEL}} = \frac{1}{m}\sum_{i=1}^{m}\mathrm{DEL}_i$$

$$\mathrm{DEL}^{'} = \frac{1}{2}\sum_{i=1}^{m}\sum_{j=1}^{n}\left|\frac{x_{ij}}{\sum_{k=1}^{m} X_k} - \frac{a_j}{mA}\right|$$

if $X_k = X_l \,\forall\, k, l \in m$, then $\sum_{k=1}^{m} X_k = mX_k$ and so

$$\mathrm{DEL}^{'} = \frac{1}{m}\sum_{i=1}^{m}\frac{1}{2}\sum_{j=1}^{n}\left|\frac{x_{ij}}{X_i} - \frac{y_{ij}}{Y_i}\right| = \frac{1}{m}\sum_{i=1}^{m}\mathrm{DEL}_i = \overline{\mathrm{DEL}}$$

Equivalence between averaging and person-hours: D

$$\mathrm{D}_i = \frac{1}{2}\sum_{j=1}^{n}\left|\frac{x_{ij}}{X_i} - \frac{y_{ij}}{Y_i}\right|$$

$$\overline{\mathrm{D}} = \frac{1}{m}\sum_{i=1}^{m}\mathrm{D}_i$$

$$\mathrm{D}^{'} = \frac{1}{2}\sum_{i=1}^{m}\sum_{j=1}^{n}\left|\frac{x_{ij}}{\sum_{k=1}^{m} X_k} - \frac{y_{ij}}{\sum_{k=1}^{m} Y_k}\right|$$

if $X_k = X_l$ and $Y_k = Y_l \;\forall\, k, l \in m$, then $\sum_{k=1}^{m} X_k = mX_k$ and $\sum_{k=1}^{m} Y_k = mY_k$ and so

$$\mathrm{D}^{'} = \frac{1}{m}\sum_{i=1}^{m}\frac{1}{2}\sum_{j=1}^{n}\left|\frac{x_{ij}}{X_i} - \frac{y_{ij}}{Y_i}\right| = \frac{1}{m}\sum_{i=1}^{m}\mathrm{D}_i = \overline{\mathrm{D}}$$

Equivalence between averaging and person-hours: ${}_x\mathbf{P}^*_y$

$${}_x\mathrm{P}^*_{yi} = \sum_{j=1}^{n}\left(\frac{x_{ij}}{X_i}\cdot\frac{y_{ij}}{t_{ij}}\right)$$

$$\overline{{}_x\mathrm{P}^*_y} = \frac{1}{m}\sum_{i=1}^{m} {}_x\mathrm{P}^*_{yi}$$

$${}_x\mathrm{P}^{*'}_{yi} = \sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{x_{ij}}{\sum_{k=1}^{m} X_k}\cdot\frac{y_{ij}}{t_{ij}}\right)$$

if $X_k = X_l \,\forall\, k, l \in m$, then $\sum_{k=1}^{m} X_k = mX_k$ and so

$${}_x\mathrm{P}^{*'}_{yi} = \frac{1}{m}\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{x_{ij}}{X_i}\cdot\frac{y_{ij}}{t_{ij}}\right) = \frac{1}{m}\sum_{i=1}^{m} {}_x\mathrm{P}^*_{yi} = \overline{{}_x\mathrm{P}^*_y}$$

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