GIS METHODS IN TIME-GEOGRAPHIC RESEARCH: GEOCOMPUTATION AND GEOVISUALIZATION OF HUMAN ACTIVITY PATTERNS

by
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ABSTRACT. Over the past 40 years or so, human activities and movements in space-time have attracted considerable research interest in geography. One of the earliest analytical perspectives for the analysis of human activity patterns and movements in space-time is time geography. Despite the usefulness of time geography in many areas of geographical research, there are very few studies that actually implemented its constructs as analytical methods up to the mid-1990s. With increasing availability of geo-referenced individual-level data and improvement in the geo-computational capabilities of Geographical Information Systems (GIS), it is now more feasible than ever before to operationalize and implement time-geographic constructs. This paper discusses recent applications of GIS-based geo-computation and three-dimensional (3-D) geo-visualization methods in time-geographic research. The usefulness of these methods is illustrated through examples drawn from the author's recent studies. The paper attempts to show that GIS provides an effective environment for implementing time-geographic constructs and for the future development of operational methods in time-geographic research.

Key words: time geography, space-time paths, GIS, geocomputation, geovisualization

Introduction

In the past 40 years or so, human activities and movements in space-time have attracted considerable research interest in geography. This research area includes a wide range of themes such as migration, residential mobility, shopping, travel and commuting behaviour. One of the earliest analytical perspectives for the analysis of human activity patterns and movements in space-time is time geography. Developed by a group of Swedish geographers – including Torsten Hägerstrand, Tommy Carlstein, Bo Lenntorp and Don Parkes – the time-geographic perspective has inspired generations of geographers and transportation researchers in the analysis of human activities in space-time.

Time geography not only highlights the importance of space for understanding the geographies of everyday life. It also allows the researcher to examine the complex interaction between space and time and their joint effect on the structure of human activity patterns in particular localities (e.g. Kwan, 1999a). This perspective has been particularly fruitful for understanding women's everyday lives because it helps to identify the restrictive effect of space-time constraints on their activity choice, job location, travel, as well as occupational and employment status (Dyck, 1990; England, 1993; Friberg, 1993; Kwan, 2000a; Laws, 1997; Palm, 1981; Tivers, 1985). Time geography has also been used as a framework for the study of migration and mobility behaviour (Odland, 1998), exposure to health risk (Löytönen, 1998), and the everyday life of children, dockworkers and homeless people (Mårtensson, 1977; Pred, 1990; Rollinson, 1998).

Despite the usefulness of time geography in many areas of geographical research, there are very few studies that actually implemented its constructs as analytical methods up to the mid-1990s – with the notable exception of Bo Lenntorp's (1976, 1978) Program Evaluating the Set of Alternative Sample Path (PESASP) simulation model. The limited development of time-geographic methods may be attributed to the lack of detailed individual-level data and analytical tools that can realistically represent the complexities of an urban environment (e.g. the transportation network and spatial distribution of urban opportunities). Another difficulty is that individual movement in space-time is a complex trajectory with many interacting dimensions. These include the location, timing, duration, sequencing and type of activities and/or trips. This characteristic of activity patterns has made the simultaneous analysis of its many dimensions difficult.

However, with increasing availability of geo-referenced individual-level data and improvement in the geo-computational capabilities of Geographical Information Systems (GIS), it is now more feasible than ever before to operationalize time-geographic constructs. Furthermore, the use of GIS also allows the incorporation of large amounts of geographic data that are essential for any meaningful analysis of human activity patterns. Because of these changes, time-geographic methods are undergoing a new phase of development as several recent studies indicate (e.g. Dijst and Vidakovic, 2000, Dijst *et al.,* 2002; Kim and Kwan, 2003; Kwan, 1998; 1999a, 1999b; Miller, 1999; Ohmori *et al.,* 1999; Takeda, 1998; Weber, 2003; Weber and Kwan, 2002, 2003). Although the primary focus of these studies is on individual accessibility, there are many areas where time geography may be fruitfully applied.

This paper explores the value of GIS-based time-geographic methods in the description and analysis of human activity patterns in space-time. It discusses recent developments in GIS-based geo-computation and three-dimensional (3-D) geo-visualization methods. Usefulness of these methods is illustrated through examples drawn from the author's recent studies. The paper attempts to show that GIS provides an effective environment for implementing time-geographic constructs and for the future development of operational methods in time-geographic research. An important premise of the paper is that the development and implementation of time-geographic concepts had been limited by the computational intensity of time-geographic modelling as well as the lack of digital geographic data. But the drastic increase in computer power and availability of digital geographic databases in recent years will greatly facilitate the application and development of time-geography methods in the future. The paper begins with a discussion of early implementation of time-geographical concepts, especially Lenntorp's PESASP simulation. Examples of GIS-based geo-computation and geo-visualization methods are discussed in subsequent sections.

Operationalization of time-geographic constructs

Time geography conceives and represents an individual's activities and travel in a 24-hour day as a continuous temporal sequence in geographical space. The number and location of everyday activities that may be performed by one person are limited by the amount of time available and the space-time constraints associated with various obligatory activities (e.g. work) and joint activities with others. Important constructs in time geography such as stations, projects, space-time paths and prism constraints are well articulated in Carlstein *et al.,* (1978), Hägerstrand (1970), Parkes and Thrift (1975) and Thrift (1977). However, the first in-depth analytical treatment and operationalization of time-geographic constructs were provided by Lenntorp (1976).

In that study Lenntorp provided a formulation of individual accessibility that centers on the notion of an individual's reach, which is the physically accessible part of the environment in space-time given the individual's constraints. This accessible portion is the space-time prism or potential path space (PPS). The projection of the prism on to planar geographic space depicts the reachable area by the individual and is called potential path area (PPA). Based on these constructs, the volume of the space-time prism (or potential path space) and the area delimited by its projection on to planar space (PPA) are used as accessibility measures. Prism volumes and areas of PPA under various conditions were derived based on the geometrical relations between the locations of origin and destination, travel speed, activity duration and time budget. Lenntorp (1976) then conducted a simulation exercise that attempted to identify all the potential space-time paths of individuals in the study area.

The study area in Lenntorp (1976) was the Vällingby-Bromma area in Sweden. The activity-travel survey data of 980 households used in the study were collected in 1967. At that time there were no digital geographic data of any sort that could be used to provide the computational framework for the simulation exercise. All the geographic data were therefore manually constructed from the ground up. As Lenntorp (1976, p. 82) reported, among the 5 500 items of information assembled for running the PESASP simulation, there were data for 496 individual stations and 138 food stores. The digital road network (called the 'link-net' (p. 84)) was also constructed from the ground up. It had a total of 100 nodes and 246 links. To construct the link-net, distances were measured manually with a distance-recording instrument on a map with a scale of 1:20 000. A total of 246 distances were measured, and they became the input for a computer program that calculated the shortest distances between all pairs of nodes.

Through this process, Lenntorp (1976) successfully established a digital multi-modal transportation network that included public transport, bicycle and walking as alternative travel mode. This was perhaps the first digital transport network constructed for the study of human activity patterns in space-time. Demand for computational resources, however, was tremendous. The data on the environment (e.g. stations and the transport network) totalled approximately 14 000 data items, and the 230 activity programs constructed contained a total of about 6 000 data items. Computing time totalled five hours and 44 minutes, and approximately 80% of this time was required for the 62 activity programs where public transport is combined with walking.

The PESASP simulation conducted by Lenntorp in the late 1970s was remarkable in the light of the limited digital geographic data and computational resources at that time. To contextualize his achievement, one may compare it with another study by Bach (1981) that evaluates accessibility using location-allocation models (the study did not use time-geographic constructs) a few years later. Bach's study dealt with 286 demand points and a much larger street network that had 939 nodes and 2 395 arcs. As reported by Bach (1981), the coding of the geographic coordinates of the demand points took two days, but the manual construction of the digital street network took about three months – although the computation of the 286 × 286 distance matrix of shortest paths in the network took only a few minutes of computer time. The time needed for constructing the geographic data for both Lenntorp and Bach had been considerable. But the duration needed for PESASP computation was in the order of 60 to 70 times longer than one that did not involve the simulation of potential space-time paths or alternative activity programs.

Implementation of time-geographic concepts is computationally demanding. Although analytical time-geographic constructs were further expanded and elaborated by Burns (1979) and Landau *et al.*, (1982), there was no operational method for implementing these constructs using data that realistically capture the complex geographies of the urban environment or the transportation network. There were some attempts to operationalize time-geographic constructs (e.g. Villoria, 1989), but they all used geometrical methods based on simplifying assumptions about the urban environment and none of them used real geographic data of urban opportunities or transportation network. There are a number of difficulties with this approach. First, mobility and travel speed were assumed to be uniform throughout the urban environment. Second, urban opportunities were assumed to be evenly distributed in the urban environment (Kwan and Hong, 1998).

For example, the space-time prism or potential path area (PPA) derived using geometric method takes the shape of a spatial ellipse whose geometric properties are determined only by the locations of a person's home and workplace and the given time budget (e.g. Kondo and Kitamura, 1987). While the ellipse may be a good appromixation of the PPA in metropolitan areas where mobility is relatively uniform, it is highly unrealistic in other urban contexts. As shown in Kwan and Hong (1998) and Weber (2003), the spatial configuration and extent of potential path area are heavily shaped by the geometry of the transportation network, often stretching along routes of high speed of travel. When mobility and travel speed are not equal in all areas and directions in a city, the spatial configuration of the PPA is far from any convenient geometric shapes such as the ellipse used to approximate the PPA in past studies.

Although Burns (1979) considered the effect of transport network on the configuration of space-time prisms, and Miller (1991) first developed a network-based algorithm for computing space-time prism and accessibility, it was not until the late 1990s that Kwan (1998) first operationalized network-based accessibility measures using a geo-computational algorithm and digital geographic data of the transportation network and urban opportunities in the study area. From this point onward, GIS-based time-geographic research seems to have evolved into an active phase of development, especially in the areas of geo-computation and 3-D geo-visualization. The following two sections discuss selected examples in these two areas from the author's recent studies.

Geo-computation of space-time accessibility measures

The term *geo-computation* refers to an array of activities involving the use of new computational tools and methods to depict geographical variations of phenomena across scales (Longley, 1998). It encompasses a wide range of computer-based techniques, including expert systems, fuzzy sets, genetic algorithms, cellular automata, neural networks, fractal modelling, visualization and data mining. Many of these methods are derived from the field of artificial intelligence and the more recently defined area of computational intelligence (Couclelis, 1998). The availability of affordable high-speed computing and the development of GIS technologies in recent years have greatly facilitated the application of geo-computation in time-geographic research.

The use of geo-computation as a time-geographic method is most visible in recent research on individual accessibility (Kwan, 1998, 1999b; Kim and Kwan, 2003; Miller, 1999; O'Sullivan *et al.*, 2000; Weber, 2003; Weber and Kwan, 2002, 2003). It involves the development and application of dedicated algorithms for computing space-time accessibility measures within a GIS environment. Space-time accessibility measures are based largely on the analytical framework formulated by Lentorp (1976) and Burns (1979). They are based on the time-geographic construct of potential path area, which is the geographic area that can be reached within the space-time constraints established by an individual's fixed activities. It is the area that an individual can physically reach after one fixed activity ends while still arriving in time for the next fixed activity. All space-time accessibility measures are derived from certain measurable attribute of this area (e.g. number of opportunities it includes).

Because of the need to represent real-world complexities and to deal with the large amount of geographic data, GIS provides an effective environment for implementing geo-computational algorithms for space-time accessibility measures. With modern GIS technologies and increasingly available disaggregate data, highly refined space-time measures of individual accessibility may be operationalized. Several studies in recent years have developed and implemented geo-computational algorithms based on the time-geographic perspective. Drawing upon the author's recent search, several examples are discussed below to illustrate the application of geo-computation in time-geographic research.

Kwan's algorithm

The first major effort in the geo-computation of space-time accessibility measures is that by Kwan (1998). The study examined individual access to urban opportunities for a sample of 39 men and 48 women in Columbus (Ohio, USA). Data for the study came from three main sources. The first source is an activity-travel diary dataset collected by the author through a mail survey in 1995. In addition to questions about the activity-travel characteristics of the respondent, data of the street addresses of all activity locations and the subjective spatial and temporal fixity ratings of all out-of-home activities were collected (Kwan, 2000a). The second source of data is a digital geographic database of the study area that provides detailed information about all land parcels, their attributes, and other geographical features of the study area. Among the 34 442 non-residential parcels in the database, 10 727 parcels belonging to seven land-use categories were selected as the urban opportunities in the study. The third data source is a detailed digital street network of the study area. The network database contains 47 194 arcs and 36 343 nodes of Columbus streets and comes with comprehensive address ranges for geo-coding locations.

Using these data, 18 conventional measures of the gravity and cumulative opportunity variants were evaluated using the home locations of the 87 individuals as origins and 10 727 property parcels as destinations. Distances were computed using point-to-point travel times through a digital street network. Three space-time measures were also computed for each individual using a geo-computational algorithm written in ARC Macro Language (AML) and implemented in ARC/INFO GIS. These three measures evaluate the size of the space that can be reached, the number of opportunities that can be reached, and the size or attractiveness of those opportunities. The algorithm used in the study was based on the one developed in Kwan and Hong (1998). Although it provides only an approximate solution to the exhaustive set of reachable opportunities, it is computationally more tractable. It uses the intersection of a series of paired arc-allocations to generate individual network-based PPAs, each of which is defined by the space-time coordinates of two fixed activities (see Fig. 1 for a schematic representation of the algorithm).

The results of the study reveal the contrast between conventional and space-time measures. While the values produced by most gravity and cumulative opportunity measures were highly correlated and produced similar spatial patterns, space-time measures were very different. Gravity measures tended to replicate the geographical patterns of urban opportunities in the study area by favouring locations near major freeway interchanges and commercial developments, while cumulative opportunity measures emphasized centrality within the city by showing the downtown area to be the most accessible place. In contrast, space-time measures produced different spatial patterns, and the patterns for men resembled the spatial distribution of opportunities in the study area while the

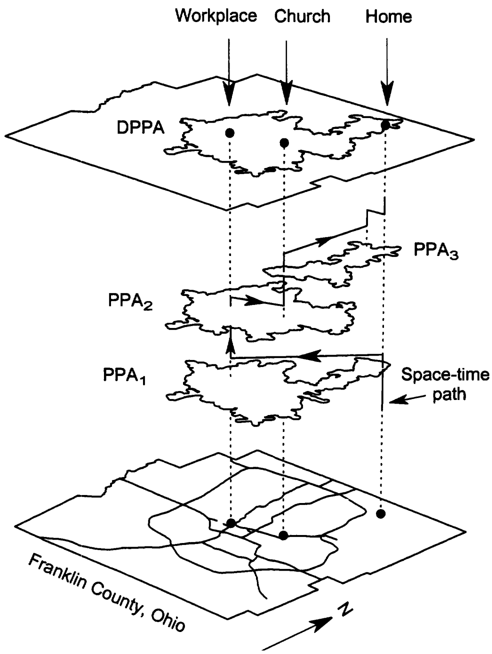

Fig. 1. A schematic representation of Kwan's algorithm.
Source: Kwan (1999). Used by permission of the Association of American Geographers.

women's patterns were considerably different. The study shows that space-time measures are capable of revealing individual differences that are invisible when using conventional accessibility measures.

Weber and Kwan's algorithm

To take into account the effect of the spatial and temporal variations in travel speeds and facility opening hours on individual accessibility, Weber and Kwan (2002, 2003) developed a second-generation algorithm for computing space-time accessibility measures. The study used a new geographic database with the enhanced geo-computational algorithm. The activity-travel diary dataset used was collected through the Activity and Travel Survey in Portland Metropolitan Area in Oregon (USA) in 1994 and 1995. The data set logged a total of 129 188 activities and 71 808 trips undertaken by 10 084 respondents. Among the respondents, 101 men and 99 women were selected for the study. Besides, a digital street network with estimates of free flow and congested travel times (with 130 141 arcs and 104 048 nodes) and a comprehensive geographic database of the study area were used. A digital geographic database containing 27 749 commercial and industrial land parcels was used to represent potential activity opportunities in the study area.

The analytical procedures involved creating a realistic representation of the temporal attributes of the transport network and urban opportunities in the study area, as well as developing a geo-computational algorithm for implementing space-time accessibility measures within a GIS environment. The algorithm was developed and implemented using Avenue, the object-oriented scripting language in the ArcView 3.2 GIS environment. Five space-time accessibility measures were computed. The first is the length of the road segments contained within the daily potential path area (DPPA). The second is the number of opportunities within the DPPA. The total area and total weighted area of the land parcels within the DPPA is the third and fourth space-time accessibility measures computed. Finally, to incorporate the effect of business hours on accessibility measures, opportunity parcels were assumed to be available (and could therefore be accessible to an individual) only from 9 a.m. to 6 p.m. This creates the fifth accessibility measure.

The results show that link-specific travel times produce very uneven accessibility patterns, with access to services and employment varying considerably within the study area. The time of day when activities were carried out has also been shown to have an effect on accessibility, as evening congestion sharply reduced individuals' access throughout the city. The effect of this congestion on mobility is highly spatially uneven. Furthermore, the use of business hours to limit access to opportunities at certain times of the day shows that non-temporally restricted accessibility measures produce inflated values by treating these opportunities as being available at all times of the day. It is not only that incorporating time reduces accessibility, but that it also produces a very different, and perhaps unexpected, geography of accessibility (Weber and Kwan, 2002). This geography depends very much on individual behaviour and so cannot be discerned from the location of opportunities or congestion alone. The study observed that the role of distance in predicting accessibility variations within cities is quite limited (Kwan and Weber, 2003).

Kim and Kwan's algorithm

In an attempt to render earlier geo-computational algorithms more realistic, several enhancements were conceived and implemented by the third-generation algorithm developed by Kim and Kwan (2003). First, space-time accessibility is extended as a measure of not only the number of accessible opportunities, but also the duration for which these facilities may be enjoyed given the space-time constraint of an individual and facility opening hours. Second, more realistic travel times are incorporated through better representation of the transportation network, such as one-way streets in downtown areas and turn prohibition – besides incorporating the effect of congestion, and location- and segment-specific travel speeds. Third, ways are developed to better incorporate other factors such as facility opening hours, minimum activity participation time, maximum travel time threshold, and delay times. The study seeks to enhance space-time accessibility measures with more rigorous representation of the temporal and spatial characteristics of opportunities and human activity-travel behaviour.

A new GIS-based geo-computational algorithm was developed to implement these enhancements. The key idea of the algorithm is to efficiently identify all of the feasible opportunities within the space-time prism using several spatial search operations in ArcView GIS, while limiting the spatial search boundary with information about the travel and activity participation time available between two fixed activities. This algorithm was developed based upon numerous tests of the computational efficiency of different methods and a series of experiments using a large activity-travel diary dataset and a digital street network. The GIS algorithm for deriving the potential path area (PPA) and for calculating space-time accessibility was implemented using Avenue in ArcView GIS. The study shows that space-time accessibility measures that do not consider the effect of facility opening hours and activity duration threshold will tend to overestimate individual accessibility.

3-D geo-visualization of human activity patterns in space-time

Geo-visualization (visualization of geographic information) is the use of concrete visual representations and human visual abilities to make spatial contexts and problems visible (MacEachren *et al.*, 1999). Through involving the geographical dimension in the visualization process, it greatly facilitates the identification and interpretation of spatial patterns and relationships in complex data in the geographical context of a particular study area. For the visualization of geographic data, conventional GIS has focused largely on the representation and analysis of geographic phenomena in two dimensions (2-D). Although 3-D visualization programmes with advanced 3-D modelling and rendering capabilities have been available for many years, they have been developed and applied in areas largely outside the GIS domain (Sheppard, 1999). Only recently has GIS incorporated the ability to visualize geographic data in 3-D (although specialized surface modelling programmes have existed for many years). This is the case not only in the digital representation of physical landscape and terrain of land surfaces, but also in the 3-D representation of geographic objects using various data structures.

Despite the use of GIS-based 3-D geo-visualization in many areas of research in recent years, its application in time-geographic research is rather limited to date. In many early studies, 2-D maps and graphical methods were used to portray the patterns of human activity-travel patterns in space-time (e.g. Chapin, 1974; Tivers, 1985). Individual daily space-time paths were represented as lines connecting various destinations. Using such kinds of 2-D graphical methods, information about the timing, duration and sequence of activities and trips was lost. Even long after the adoption of the theoretical constructs of the time-geographic perspective by many researchers in the 1970s and 1980s, the 3-D representation of space-time aquariums and space-time paths seldom went beyond the schematic representations used either to explain the logic of a particular behavioural model or to put forward a theoretical argument about human activity patterns. They were not intended to portray the real experience of individuals in relation to the concrete geographical context in any empirical sense.

There have, however, been noticeable changes in recent years. As more geo-referenced activity-travel diary data become available, and as more GIS software has incorporated 3-D capabilities, GIS-based 3-D geo-visualization has become a more feasible approach to time-geographic research. For instance, Forer (1998) implemented space-time paths and prism on a 3-D raster data structure for visualizaton and computational purposes. Their method is useful for aggregating individuals with similar socioeconomic characteristics and for identifying behavioural patterns. Kwan (2000b) and Kwan and Lee (2004) implemented 3-D visualization of space-time paths and aquariums using vector GIS methods and activity-travel diary data. These studies indicate that GIS-based geo-visualization can be a fruitful method for time-geographic research. Furthermore, implementing 3-D visualization of human activity patterns can be an important first step in the development of GIS-based geo-computational procedures that are applicable in many areas of geographical research. The following subsections provide an overview of some of these methods from the author's recent research.

Space-time paths and the space-time aquarium

The earliest 3-D method for the visualization of individual space-time paths is the space-time aquarium conceived by Hägerstrand (1970). In a schematic representation of the aquarium, the vertical axis is the time of day and the boundary of the horizontal plane represents the spatial scope of the study area. Individual space-time paths are portrayed as trajectories in this 3-D aquarium. Although the schematic representation of the space-time aquarium was developed long ago, it has never been implemented using real activity-travel diary data. The main difficulties include the need to convert the activity data into '3-Dable' formats that may be used by existing visualization software, and the lack of comprehensive geographic data for representing complex geographic objects of the urban environment.

Kwan (1999a) was the first to implement the space-time aquarium and space-time paths in a 3-D GIS environment using individual-level activity-travel diary data. Based on a subsample of 72 European Americans from the dataset she collected in Columbus (Ohio, USA), the study examines the effect of gender on the space-time patterns of out-of-home non-employment activities. Visualization of the space-time paths of three groups of research participants reveals their distinctive activity patterns, and this insight guided the structural equation modelling in the later phase of the study. The results of the study show that the structure of one's daily activity patterns and daytime fixity constraint depends more on one's gender than on some conventional variables of household responsibilities such as the presence or number of children in the household.

Given the limited 3-D visualization capabilities of GIS when the study was conducted, the geo-visualization performed by Kwan (1999a) did not use a large geographic database of the study area (but it did incorporate a transportation network). The first study to incorporate a comprehensive geographic database for the 3-D geo-visualization of space-time paths was that of Kwan (2000b). This study used the Portland activity-travel diary dataset mentioned above and a comprehensive geographic database of the Portland metropolitan region (Oregon, USA). The GIS database provides comprehensive data on many aspects of the urban environment and transportation system of the study area. It has data for about 400 000 land parcels in the study area. The digital street network used, with 130 141 arcs and 104 048 nodes, covers the four counties of the study area (i.e. Clark, Clackamas, Multnomah and Washington).

These contextual data allow the activity-travel data to be related to the geographical environment of the region during visualization. To implement 3-D geo-visualization of the space-time aquarium, four contextual geographic data layers are first converted from 2-D map layers to 3-D format and added to a 3-D scene. These include the metropolitan boundary, freeways, major arterials and rivers. For better close-up visualization and for improving the realism of the scene, outlines of commercial and industrial parcels in the study area are converted to 3-D polygons and vertically extruded in the scene. Finally, the 3-D space-time paths of the African and Asian Americans in the sample are generated and added to the 3-D scene. These procedures finally created the scene shown in Fig. 2.

The overall pattern of the space-time paths for these two groups shown in Fig. 2 indicates heavy concentration of daytime activities in and around downtown Portland. Using the interactive visualization capabilities of the 3-D GIS, it was observed that many individuals in these two ethnic groups work in downtown Portland and undertake a considerable amount of their non-employment activities in areas within and east of the area. Space-time paths for individuals who undertook several non-employment activities in a sequence within a single day tend to be more fragmented than those who work long hours during the day. Furthermore, ethnic differences in the spatial distribution of workplace are observed using the interactive capabilities provided by the geo-visualization environment. The space-time paths of Asian Americans are more spatially scattered throughout the area than those of the African Americans, whose work and non-employment activities are largely concentrated in the east side of the metropolitan region.

A close-up view from the west of the 3-D scene is given in Fig. 3, which shows some of the details

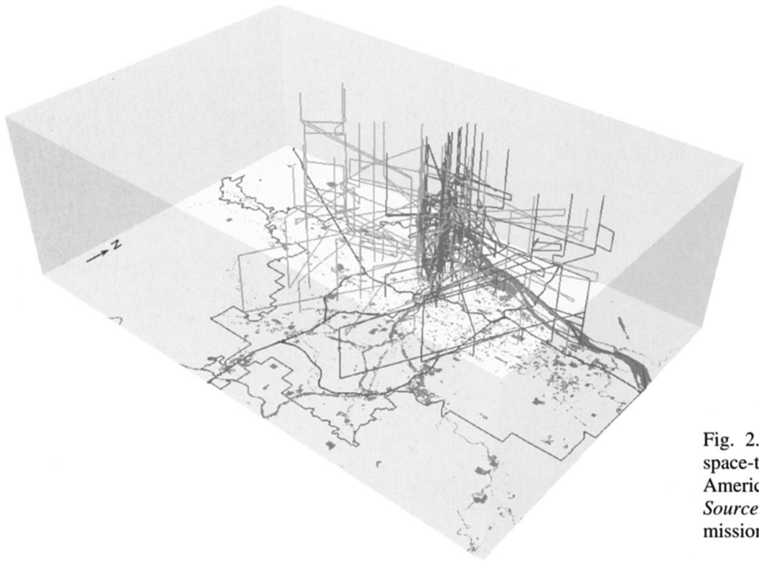

Fig. 2. Space-time aquarium showing the space-time paths of African and Asian Americans in the sample.
Source: Kwan and Lee (2004). Used by permission of Oxford University Press, Inc

of downtown Portland in areas within and around the 'loop' and along the Willamette River. Portions of some space-time paths may also be seen. With the 3-D parcels and other contextual layers in view, the figure gives the researcher a strong sense about the geographical context through a virtual reality-like view of the downtown area.

Space-time paths based on GPS data

Although the 3-D space-time paths shown in Figs 2 and 3 are helpful in understanding the activity patterns of different population subgroups, these paths are not entirely realistic since they only connect trip ends with straight lines and do not trace the travel routes of an individual. This limitation is due to the lack of route data in the Portland dataset. When geo-referenced activity-travel data collected by GPS are available and used in the geo-visualization environment, the researcher can examine the detailed characteristics of an individual's travel pattern, since actual travel routes can be revealed by these kinds of data (Kwan, 2000c; Kwan and Lee, 2004). Fig. 4 illustrates this possibility using the GPS data collected in the Lexington Area Travel Data Collection Test conducted in 1997 (Battelle, 1997). The original dataset contains information on 216 licensed drivers (100 male, 116 female) from 100 households with an average age of 42.5 years. In total, data of 2 758 GPS-recorded trips and 794 861 data points of latitude–longitude pairs and time were collected for a six-day period for each survey participant.

To prepare for 3-D geo-visualization, three contextual geographic data layers of the Lexington metropolitan area are first converted from 2-D map layers to 3-D format and added to a 3-D scene. These include the boundary of the Lexington metropolitan region, highways and major arterials. As an illustration, the 3-D space-time paths of the women with no children under 16 years of age in the sample are generated and added to the 3-D scene. These procedures finally created the scene shown in Fig. 4. The overall pattern of the space-time paths for these women indicates that their trips were undertaken using largely highways and major arterials. There is some regularity as indicated by the daily repetition of trips in more or less the same time throughout the six-day survey period. This suggests that distinctive activity-travel patterns can be revealed by 3-D geo-visualization.

There are difficulties in the analysis of these GPS data due to the computational intensity of processing and visualizing large space-time datasets (Kwan, 2001a; Lowe, 2003). For instance, the original GPS data file for the 100 households contains 794 861 data points of latitude–longitude pairs and time (Kwan, 2000c; Murakami and Wagner, 1999). It takes up about 230 megabytes of disk space in the format provided on the data CD. Ma-

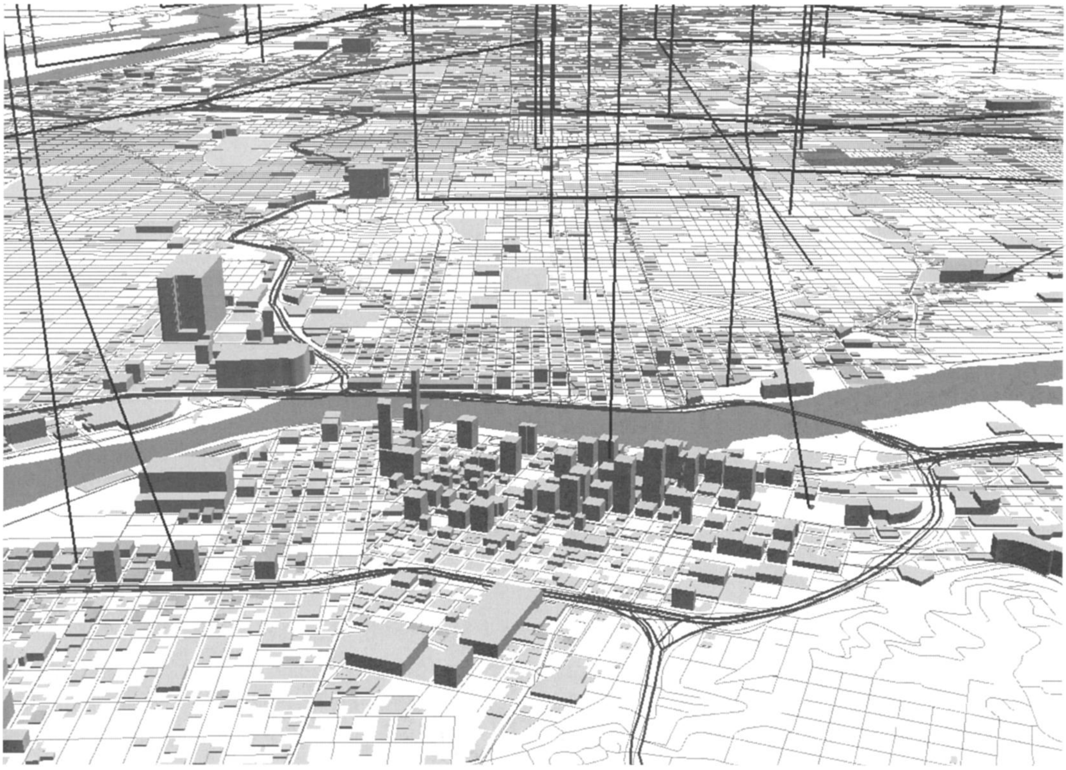

Fig. 3. A close-up view of downtown Portland.
Source: Kwan and Lee (2004). Used by permission of Oxford University Press, Inc.

nipulating files of this size can be taxing for the computer hardware normally available to social scientists. Although improvement in computing power in the near future will reduce this problem, more research is still needed to develop more efficient algorithms and data manipulation methods for handling large GPS datasets.

Human extensibility and cyberspatial activities in space-time

Three-dimensional geovisualization has also been applied to visualize human activities in both the physical world and cyberspace based on the notion of human extensibility (Kwan, 2000d). The concept of the individual as an extensible agent was first formulated by Janelle (1973), where extensibility represents the ability of a person to overcome the friction of distance through using space-adjusting technologies, such as transportation and communication. Human extensibility not only expands a person's scope of sensory access and knowledge acquisition; it also enables a person to engage in distantiated social actions whose effect may extend across disparate geographical regions or historical episodes (Kwan, 2001b). To depict human extensibility that includes activities both in the physical world and cyberspace, Adams (1995) developed the extensibility diagram using the cartographic medium. The diagram, based on Hägerstrand's space-time aquarium, portrays a person's daily activities and interactions with others as multiple and branching space-time paths in three dimensions, where simultaneity and temporal disjuncture of different activities is revealed. This method may be used to represent a diverse range of human activities both in the physical and virtual worlds, including telephoning, driving, e-mailing, reading, remembering, meeting face-to-face and television viewing.

Although the extensibility diagram is largely a cartographic device, most of its elements are amenable to GIS implementation. Kwan (2000d) developed a method for implementing the extensi-

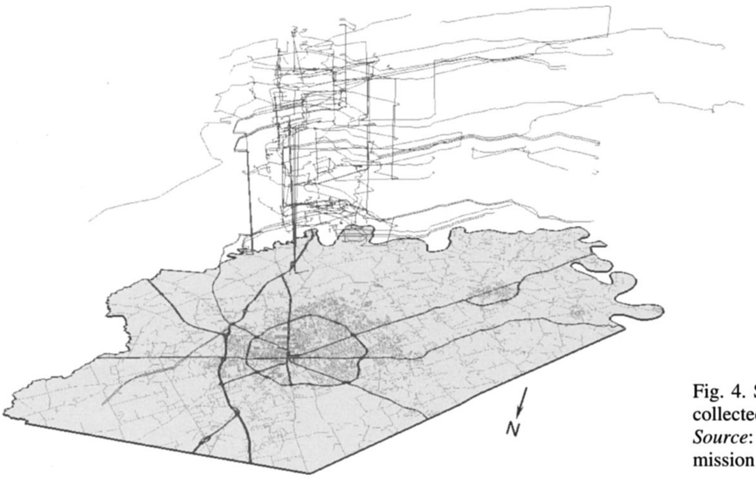

Fig. 4. Space-time paths based on GPS data collected in Lexington, Kentucky.
Source: Kwan and Lee (2004). Used by permission of Oxford University Press, Inc.)

bility diagram using 3-D GIS. The study used real data about a person's physical activities and cyberspatial activities (e.g. e-mail messages and web-browsing sessions). The focus is on incorporating the multiple spatial scales and temporal complexities (e.g. simultaneity and disjuncture) involved in individual hybrid accessibility. The following example, derived from the case examined in Kwan (2000d), illustrates the procedures for constructing the multi-scale 3-D extensibility diagram and its use in a GIS-based 3-D geo-visualization environment. The first step is to determine the most appropriate spatial scales and to extract the relevant base maps from various digital sources.

Consider a person who lives and works in Franklin County (Ohio, USA), and engages in cyberspatial activities (e.g. sending and receiving e-mail) involving cities in the northeastern region of the USA and other countries (e.g. South Africa and Japan). To prepare the GIS base maps at these three spatial scales (local, regional and global), a map of Franklin County and a regional map of 15 US states in the northeastern part of the country were first extracted from a commercial geographic database. Franklin County is the home county of the person in question, whereas the US region extracted will be used to locate the three American cities involved in her cyber-transactions. These cities are Chicago in Illinois, Maywood in New Jersey and Charlotte in North Carolina. At the global scale, the world map layer was derived from the digital map data that came with ArcView GIS (many high-latitude regions and islands in the world map layer were eliminated to improve visual clarify).

After performing map-scale transformations to register these three map layers to the person's home location in Franklin County, these 2-D map layers were converted to 3-D shape files and added to an ArcView 3-D Analyst scene as 3-D themes. After preparing these map layers, 3-D shape files for the person's space-time paths were generated using Avenue scripts and added to the 3-D scene. These procedures finally created the multi-scale extensibility diagram shown in Fig. 5. It shows how various types of transactions at different spatial scales may be represented in a 3-D GIS environment.

Figure 5 shows five types of activities undertaken on a particular day. On this day, the person in question worked from 8.30 a.m. to 5.30 p.m., and had a one-hour lunch break at a nearby restaurant (c in the diagram). She subscribes to a Web-casting service where news is continuously forwarded to her web browser. On this day, she read some news about Yugoslavia, South Africa and Nashville, TN (a in the diagram) before she started work. An hour later she sent an e-mail message to three friends located in Hong Kong, Chicago and Vancouver (b). The friend in Chicago read the e-mail two hours later and the friend in Vancouver read the email five hours later. The friend in Hong Kong read the e-mail 13 hours later and replied immediately (e). The reply message from this friend, however, was read at 2.00 a.m. at the person's home (g). In the afternoon, she browsed web pages hosted in New

York, Charlotte and Anchorage in Alaska (d). She finished work at 5.30 p.m. and spent the evening at home. At 9.00 p.m. she started an ICQ (real-time chat) session with friends in Tokyo, Melbourne, Memphis, TN, and Dublin, OH (f on the diagram).

As shown in Fig. 5, very complex interaction patterns in cyberspace can be represented using multiple and branching space-time paths. These include temporally coincidental (real-time chat) and temporally non-coincidental (e-mailing) interactions; one-way radial (web browsing), two-way dyadic or radial (e-mailing), and multi-way (chat) interactions; incoming (web casting) and outgoing (e-mailing) transactions. The method is thus capable of capturing the spatial, temporal and morphological complexities of a person's extensibility in cyberspace.

Furthermore, the visualization functions available in ArcView 3-D Analyst also enable one to explore interactively the 3-D scene in a very flexible manner (e.g. the scene is visible in real-time while zooming in and out, or rotating). This allows for the selection of the best viewing angle and is a very helpful feature, especially when visualizing very complex space-time paths. To focus on only one type of transaction or activity at a particular spatial scale, one can select the relevant themes for display while keeping the other themes turned off. Furthermore, when the three sets of paths and base maps are displayed at the same time, they may be colour-coded to facilitate the visualization. In the original color 3-D scene, each segment of the space-time paths is represented using the same colour as the relevant base map (e.g. blue for Franklin County and local activities), conveying a rather clear picture of the spatiality and temporal rhythm characterizing the person's activities on that day. But in the black-and-white version presented in Fig. 5, spike lines are used to identify the location involved in each transaction.

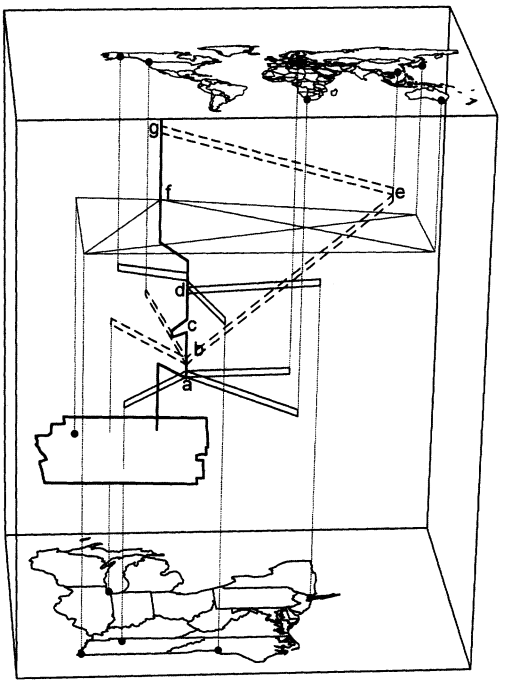

Fig. 5. An extensibility diagram rendered using 3-D GIS.
Source: Kwan (2000d). Used by permission of Springer-Verlag.

Conclusion

Despite the usefulness of time geography in many areas of geographical research, there are very few studies that actually implemented its constructs as analytical methods up to the mid-1990s. However, with increasing availability of geo-referenced individual-level data and improvement in the representational and geo-computational capabilities of Geographical Information Systems (GIS), it is now more feasible than ever before to operationalize and implement time-geographic constructs. Due to these recent changes, GIS-based time-geographic methods are undergoing a new phase of development. Drawing upon the author's recent research, this paper discusses two major areas of such development: geo-computation of individual space-time accessibility and 3-D geo-visualization of human activity patterns.

Geocomputation of individual accessibility has progressed from Kwan's first generation algorithm to Kim and Kwan's third generation algorithm. There are changes in certain aspects of these recent exercises: (1) the amount of digital geographic data used has become much larger; (2) the computing platform has moved from UNIX platform to desk-top PCs; and (3) the GIS software used has evolved from text-based ARC/INFO to Windows-based ArcView 3.x. Although the computing power available today is much better than before, the data requirement and computational intensity of the spatial search involved in the geo-computation of individual accessibility is still a major difficulty in this area of research. Both studies by Weber and Kwan (2002, 2003) and Kim and Kwan (2003) involved several months of intensive geo-computation. Although Kim and Kwan's current research is adopting concepts of massively parallel processing in the computational part of the work, there seems to be no simple solution to the problem in the near future, and the challenge remains significant for researchers involved in this kind of computational work.

With regard to GIS-based 3-D geo-visualization of human activity patterns, there are also several difficulties. First, there is the challenge of converting many types of data into '3-Dable' formats for a particular geo-visualization environment. Since every visualization software may have its unique data format requirements, and the activity and geographic data currently available are largely in 2-D format, the data preparation and conversion process can be time consuming and costly. Second, the researcher may encounter barriers to the effective visualization of large and complex activity-travel datasets. These barriers include problems associated with the limitation in human ability to identify patterns and relations when many layers, themes or variables are simultaneously viewed; the complexity associated with the vast range of possibilities that a visualization environment provides; and the orientation of the user in a visualized scene or virtual world.

Besides, rendering speed can also be a significant challenge to researchers who want to use this kind of method. For instance, interactive geo-visualizations of the Portland dataset were conducted with the help of a professional-grade graphic card, which has a dual-pipeline architecture and a highly tuned geometry engine, and is capable of rendering 24.2 million solid-colour 3-D vectors per second and has a tri-linear textured fill rate of 332 million pixels per second. But rendering 400 000 parcels or buildings (typical of a medium-sized city) in 3-D has been quite taxing, even with this high-end graphic card. Third, the use of individual-level activity-travel data geo-coded to street addresses, given their reasonable degree of positional accuracy, may lead to considerable risk of privacy violation. Researchers using the 3-D geo-visualization methods discussed in the paper should pay particular attention to this potential risk.

To conclude, Lenntorp has laid much of the analytical foundation of today's GIS-based time-geographic research. His implementation of the PESASP simulation model was remarkable in many regards. It has inspired many of the time-geographic methods discussed in this paper. Operationalization of analytical time-geographic methods, however, has been hindered by the computational demand of the tasks. Recent developments have overcome many hurdles. But it is often easy to forget past achievements that were stunning even by today's standards. Similarly, it is often easy to underestimate the breakthroughs achieved by recent GIS-based time-geographic studies that involve an enormous amount of digital data and months of computation.

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