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An Integrated Spatio-temporal GIS Toolkit for Exploring Intra-household Interactions

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Abstract

This paper reports on the development of an integrated spatio-temporal GIS toolkit that facilitates the exploration of intra-household interactions. Two tools comprise the toolkit. The first tool, Space-Time Coincidence Analyst, identifies joint activity/travel episodes undertaken by household members. The core of this tool is a set of flexible criteria for classifying episodes as either joint or independent. The second tool, Space-Time Path Visualizer, not only displays space-time paths for household members, but also shows joint episodes undertaken by any two household members together. The toolkit can be applied to any household-based, activity/travel data set so long as required information is specified by the user. To demonstrate its usefulness for research, the toolkit is applied to the TAPS (Toronto Activity Panel Survey) 2002-03 data set. The results suggest that considerable variation exists in the number of joint activity/travel episodes identified using different classification criteria. Specifically, when using restrictive criteria (i.e., same timing, specific activity type/travel mode), only 2,265 joint activity/travel episodes are identified compared to 8,792 when using more flexible criteria. In turn, our results show that certain key attributes for independent and joint activity/travel episodes (i.e., frequency per household, starting time, ending time and duration) also vary under the different classification criteria.

Keywords: *3D, Activity analysis, Geovisualization, GIS, Intra-household interaction, Joint activity, Space-time path, Spatio-temporal GIS, Travel behavior*

1. Introduction

A fundamental tenet of the activity-based approach is its focus on sequences or patterns of activity/travel behavior in the context of space, time and interpersonal constraints rather than discrete trips (Kitamura 1996). In other words, the spatio-temporal constraints imposed upon one member's activities could influence the activities of other members within a household (Shaw and Wang 2000). Therefore, the activity-based approach creates the need to "obtain a wide variety of household information and to take account of linkages among trip making and activity behavior for all household members" (Jones et al. 1990).

Household members interact in different ways when making their activity/travel decisions. Specifically, Srinivasan and Bhat (2005) summarize four general types of intra-household interactions: sharing of household maintenance obligations, joint engagement in other activities and travel, offering pick-up and drop-off services to household members with restricted mobility, and sharing the use of family vehicles. The motivations of joint participation proposed by Townsend (1987) have been widely acknowledged. These include efficiency, companionship and power/altruism. Activities and travel involving other household members result from a collective decision-making process that requires its participants to fit periods of joint episodes into individual schedules while considering their own needs and those of others (Gliebe and Koppelman 2005). Insight into intra-household interactions will benefit other related research such as the activity scheduling process of household members, and its dynamic pattern between weekday and weekend. Explicit recognition of joint episodes in the underlying scheduling process is also crucial to improving activity-based and tour-based travel demand forecasting models, thus making them even more capable of capturing responses to policy changes in land-use and transportation systems (Bhat and Pendyala 2005).

In recent years, recognition of the importance of intra-household interactions has produced a growing body of research (Bradley and Vovsha 2005; Gliebe and Koppelman 2002; Gliebe and Koppelman 2005; Goulias and Hensen 2006; Hollander and Prashker 2006; Scott and Kanaroglou 2002; Srinivasan and Athuru 2005; Srinivasan and Bhat 2006). Despite this, however, several issues have not been well addressed. One such issue concerns the identification of joint activity/travel episodes. In most studies, this is done by stipulating the same purpose/travel mode, exact location (in the case of activities), exact timing and exact duration, which we, like Gliebe and Koppelman (2002) before us, argue may be too restrictive. Simply put, some episodes that are joint in reality may be misclassified as independent when using such criteria. The following example is a case in point. Two householders (a couple) drive separately to the same restaurant for dinner. However, one arrives ten minutes earlier than the other. In this instance, according to the criteria outlined above, the householders' dinner episodes would be classified as independent simply because they do not overlap with one another in terms of timing. To identify all occurrences of joint episodes, such as the one above, more flexible criteria must be developed. Furthermore, such criteria must be automated via computer-based technology to reduce the costs (both time and money) associated with processing large household-based, activity/travel data sets to identify joint episodes. Geographic information systems (GISs) are ideally suited to this task given their unique ability to store, process, analyze and display vast quantities of georeferenced data. Moreover, they have a proven track record in activity-based research (Kwan 2004; Scott 2006).

Another issue concerns the geovisualization (visualization of geographic information) of intra-household interactions in 3D. Previous research efforts, at most, displayed co-located activities in space and time, which are not necessarily joint due to lack of a third criterion – activity type (e.g., Buliung and Kanaroglou 2006). As noted by Kwan (2000), geovisualization of activity/travel data is an effective exploratory tool that often leads to more focused research. Moreover, she argues that geovisualization can assist in formulating realistic computational or behavioral activity/travel models.

In response to the issues noted above, this paper reports on the development of an integrated spatio-temporal GIS toolkit that facilitates the exploration of intra-household interactions by identifying and visualizing (3D) joint activity/travel episodes. Past research relating to these topics is reviewed briefly in the following two sections. We then present the spatio-temporal GIS design underlying the toolkit. This is followed by a brief discussion concerning its implementation in ArcGIS (version 9.1), a GIS software package developed and distributed by ESRI. The usefulness of the toolkit is demonstrated via an empirical study using the TAPS (Toronto Activity Panel Survey) 2002-03 data set. The results from the study are documented. The paper concludes by summarizing both the functionality and limitations of the toolkit.

2. Identification of Joint Episodes

In the past, many activity/travel surveys have failed to collect information on involved persons. This has been especially true for the large-scale, trip-based surveys that underpin urban travel demand models around the world. Although this appears to be changing, even if collected, such information, without proper validation, may not be reliable due to recall errors by sampled individuals. Furthermore, in existing household-based, activity/travel surveys, the attributes of episodes (i.e., activity type/travel mode, start time, end time, duration, location) that are joint in nature may be reported differently by household members involved when, in fact, they should be the same. Given these issues, care must be exercised when identifying joint episodes for research. In essence, such episodes should be identified based on information that is both reliable and readily available in most surveys. That is to say, criteria must be developed for classifying entire episodes or parts thereof as either joint or independent. Strictly speaking, joint episodes should meet conditions of joint-in-purpose/mode (activity type/travel mode), joint-in-location, and joint-in-time. Purpose/mode, location and time are all readily available in activity/travel surveys of the past and the present, although the level of detail concerning their reporting can vary from one survey to the next. Gliebe and Koppelman (2005) suggest that joint episodes should be identified by comparing reported starting and ending times, origin and destination locations, trip purposes, travel modes, driver/rider status and passenger relationships for each household member's daily trip records. However, inconsistent reporting about starting and ending times, different perceptions of activity purposes by household members, along with other ambiguities involved in a survey data set, will likely underestimate the number of joint episodes. While this problem may be addressed to some extent in future surveys by improving survey techniques to acquire and validate explicitly joint activities and travel among household members, the techniques may prove costly to implement in terms of time and money. Moreover, undue burden will necessarily be placed on survey respondents. One means to overcome issues concerning the identification of joint activity/travel episodes in past, present and future surveys is to develop "more proximate matching criteria to include joint [episodes] that are not reported identically by household members, but have enough in common to be safely categorized as joint" (Gliebe and Koppelman 2002).

Miller (2005) describes a partial solution for identifying joint episodes by using time geography's bundle concept, which requires that during a time interval (t'_B, t''_B) two individual space-time paths must share the time interval, which means that a path can only start (C_S) or end (C_E) at the interval boundaries or outside the interval – that is, $C_S \leq t'_B \wedge C_E \geq t''_B$. This condition helps relax the joint-in-time criterion without requiring the same timing by two paths. Also, both paths must be proximal for the interval (t'_B, t''_B).

In the context of information and communication technologies (ICT), Yu (2006) uses the bundle concept to identify four patterns of human interaction using space-time paths: co-location in space, co-location in time, co-existence in both space and time, and no co-location in either space or time. A GIS-based tool is developed to detect these forms of human interaction.

Unfortunately, however, it is implemented for individuals rather than households, and thus, by design, is unable to identify joint activity/travel episodes. Also, as mentioned earlier, identification of such episodes requires comparison of a third criterion – namely, activity type or mode. The tool does not incorporate such a comparison.

In an earlier effort aimed at detecting joint trips in the Mobidrive data set, Singhi (2001) developed a C++ program that compared trips of household members based on a set of criteria including study code, city code, day of reporting and trip mode. In addition, to account for recall or encoding errors, the temporal gap in arrival and departure times had to be less than five minutes. This interval was chosen over others (i.e., zero and 10 minutes) because, apparently, it detected the maximum number of joint trips1. The only possible shortcoming of this approach as applied to the Mobidrive data set is that the joint-in-location criterion is not guaranteed. Quite simply, location is defined very broadly in terms of two German cities – Halle and Karlsruhe. Moreover, it is unclear from Singhi's work whether location applies to the origin or destination of the trip, or both. At the same time, however, the program can be easily enhanced to overcome this possible shortcoming by comparing location at a higher level of detail.

It is clear from the literature that there exists an urgent need to advance the identification of joint activity/travel episodes. To ensure that all occurrences of joint episodes are accounted for, it is necessary to relax restrictive criteria (i.e., same timing, specific activity type/travel mode) to allow for issues such as inconsistent reporting of starting and ending times, and different perceptions of activity purposes and travel modes by household members, along with other ambiguities involved in a survey data set. We refer to this new set of criteria as flexible (i.e., proximate timing, general activity type/travel mode).

3. Space-time path visualization

In many studies, to facilitate the exploration of human activity/travel behavior, individual daily space-time paths were represented as lines connecting various destinations by using 2D maps or graphical methods (e.g., Chapin 1974). One limitation of such representation is that certain important attributes of activities and trips such as timing, duration and sequencing failed to be well kept (Kwan 2000). Some recent efforts attempt to incorporate these attributes by developing more effective database management approaches (Shaw and Wang 2000; Wang and Cheng 2001). In other words, at the data organization level, the aim is to store and manage efficiently all attributes associated with the data such that redundancy is minimized while retaining complex relationships among data.

Geovisualization (visualization of geographic information) is the use of concrete visual representations and human visual abilities to make spatial contexts visible (Maceachren et

[1] It is unclear how a five-minute gap in arrival and departure times can produce more joint trips than a 10-minute gap, as reported in Singhi (2001). One would expect either the same number of trips or more trips, not fewer trips.

al. 1999). A space-time path is essentially a linear feature, describing an individual's movements in physical space over time. Unlike the other approaches mentioned above, it allows for a comprehensive presentation of information on spatio-temporal characteristics of an individual's actions, including the starting/ending times and locations of activities, the duration and the sequence of activities. In other words, the space-time path concept offers an effective approach to analyzing individuals' activities in a spatio-temporal context (Miller 2005). The concept of "bundle" has recently been recognized as an efficient way to illustrate interactions within households (Hägerstrand 1970; Miller 2005), which contributes to an understanding of household roles and responsibilities (Miller 2005). Bundling often occurs when two or more space-time paths converge for a shared activity, implying that the paths are vertical and the individuals are stationary in space. However, it also happens that two separate paths bundle during movement, examples of which include two individuals carpooling or taking a bus together (Miller 2005). With the ability of GIS to implement the space-time path and bundle concepts, and the availability of more activity/travel diary data, GIS-based 3D geovisualization has been widely recognized as a potential approach to exploring spatio-temporal characteristics of human activity/travel patterns (Kwan 2000; Pipkin 1995). The advantages of using 3D geovisualization for such exploration are summarized by Kwan (2000).

Buliung and Kanaroglou (2006) developed a household trajectories tool, which can automatically construct household space-time path data structures for all householders over a period of time. At the daily scale, xy coordinates of activity sites visited by household members are used to define locations in 2D while the timing information associated with these activities define locations in time. However, the geovisualization function demonstrated is limited to individual space-time paths, but not joint paths, the pattern of which will enhance our understanding of intra-household interactions. Another thing to note is that their tool is tied to the data set they used, which is the 1994/1995 Portland Household Activity and Travel Behavior Survey. Therefore, adaptation is needed when applying the tool to other activity/travel surveys.

4. Spatio-temporal GIS design

As discussed above, the identification of joint episodes should meet three criteria: joint-in-purpose (activity type/travel mode), joint-in-time and joint-in-location, which, for reasons given, can be restrictive. Therefore, flexible criteria have to be developed to include all joint occurrences of human activity/travel behavior within a household, by relaxing one or all of the above criteria. For the joint-in-location criterion, one possible way to make it flexible is through buffering. However, this might overestimate the number of joint episodes by mistakenly classifying different places as the same one. Therefore, the flexible criteria developed here focus on the relaxation of timing and activity type/travel mode[2] by assuming that all joint

[2] For timing, relaxation means that our flexible criteria allow a slightly different gap in starting/ending times. When it comes to activity type/travel mode, relaxation refers to

episodes should share the same location. Steps 1 to 3 describe how the criteria are implemented.

Step 1: To meet the criterion of joint-in-location, a method called Intersect is used to identify all activity/travel episodes with the same location (Yu 2006). Due to lack of a 3D intersect approach, all activity and travel episodes have to be analyzed respectively in the 2D plane.

Step 2: Fig. 1a and 1b illustrate how the temporal overlap of potential joint activity and travel episodes are identified respectively when the joint-in-location criterion is met. A_1, A_2, B_1, and B_2 represent the starting and ending times for person A (black line) and person B (grey line), respectively. t refers to the temporal overlap or joint time period shared by two people. t_1 and t_2 indicates the temporal gap of the starting times and that of ending times by two persons, respectively. For illustration purposes only, the joint activity and joint travel episodes are each represented as two separate lines (i.e., one per individual) when in fact they overlap in space. The temporal overlap only happens when $A_1 \le B_2$ and $B_1 \le A_2$. This means that the starting time of an activity by one person is no later than the ending time of an activity by another person. Furthermore, the actual temporal overlap, or the lasting time period of this joint activity starts from the moment of maximum (A_1, B_1), and ends at minimum (A_2, B_2) (Yu 2006). Joint travel, different from joint activities, has to meet the constraining condition, which requires that the temporal gap, t_1 and t_2 should be less than a small value, if not equal to 0. Such relaxation might help reduce the impact of recalling errors by sampled individuals. Although Singhi (2001) proposed applying a 5-minute interval to a six-week travel survey conducted in Germany (Axhausen et al. 2002), in our approach, the decision is left to the user, who knows the accuracy of his/her data.

<Insert Fig. 1>

Step 3: Besides the location and temporal criteria, activity type/travel mode is an imperative part of the flexible criteria. If the classification scheme used in a survey is too detailed, sampled individuals might classify the same activity into different types, due to different perceptions or recalling. For instance, a couple goes shopping together – the husband might label the activity as simply shopping, while the wife might label the same activity as shopping for clothes. Consequently, this activity cannot be classified as joint. One way to relax this criterion is reclassifying disaggregate activity types/travel modes into more generic groups (in the above example, shopping for clothes is reclassified as shopping). One example of such a classification scheme, which is employed in our empirical analysis, is: night sleep, meals, work/school, family obligations, drop-off/pick-up, shopping, services, active recreation, entertainment, and social.

activities/modes that belong to different types if applying more disaggregate classification schemes, but share the same type/mode if applying more aggregate classification schemes.

5. Implementation of the design in ArcGIS

ArcGIS and ArcObjects are chosen as the development environment for our tool for several reasons. First, a geographic information system (GIS) is able to integrate a large amount of geographic data from different sources and then solve spatial problems (Kwan 2000). Second, the ArcScene module in ArcGIS, which supports representation and visualization of 3D spatial features, is amenable to the 3D data structure (2D space + time) required by the time geography framework with time replacing altitude or elevation. Furthermore, it is very easy to exploit the available visualization functions embedded in the ArcScene platform such as zooming in, zooming out, rotating, and so on. Finally, ArcObjects offers a programming environment to develop new spatio-temporal analysis functions (Yu 2006).

The integrated space-time GIS approach is implemented through two tools in the ArcGIS 9.1 software platform: one is called *Space-Time Coincidence Analyst*, which is embedded in ArcMap, and the other is called *Space-Time Path Visualizer*, which is embedded in ArcScene. In ArcMap, intra-household interactions (represented as joint activity/travel episodes) are identified by using both the traditional restrictive criteria and our newly developed flexible criteria. Joint episodes are then exported as a database file according to household types (i.e., single with children, couple with children, and couple without children). ArcScene is used to visualize individual space-time paths, analyze relationships of such paths at the household level and then visualize joint episodes undertaken by household members. Visual Basic for Applications (VBA) programs with ArcObjects is used in our toolkit to generate the customized user interfaces and functions. The toolkit incorporates functions for generating/visualizing patterns of human activity/travel, which are represented as individual space-time paths in 3D, and functions for identifying/visualizing intra-household interactions for any two household members, which are represented as joint space-time paths in 3D. Furthermore, our tool is able to extract the exact joint time period for those joint activities by two household members who do not have the same starting times and/or ending times. The rest of this section describes how these two tools and their functions are implemented in ArcGIS and how they help explore the spatio-temporal characteristics of human activities and interactions.

Space-Time Coincidence Analyst Tool

The Space-Time Coincidence Analyst toolkit identifies joint activity/travel episodes for any two household members using both the traditional restrictive criteria and our newly developed flexible criteria. Joint episodes are exported as a database file according to household types (i.e., single with children, couple with children, and couple without children), specified by the user. This toolkit has five components, which are: 1) Import File, 2) Joint Analysis, 3) Join, 4) Query, and 5) Open ArcScene, which builds a connection to the ArcScene window. Details about each component are described in the appendix.

Space-Time Path Visualizer Tool

This Space-Time Path Visualizer tool has three components: 1) Import File. 2) Individual Path Creation, and 3) Joint Path Creation. The first function this tool provides is creating an individual space-time path for each household member in 3D. Another function supported by this tool is creating joint paths by multiple householders, which is decomposed into two interrelated steps: the identification and visualization of joint episodes in 3D. The pattern of these joint episodes in space and time can serve to better understand intra-household interactions and/or generate hypotheses for further testing. However, the user can be easily overwhelmed by the data displayed given the limits of human visual discrimination.

6. Empirical study

To demonstrate the usefulness of the toolkit, we conduct an empirical study to compare several key attributes (i.e., frequency, starting/ending time and duration) of individual and joint episodes using restrictive and flexible criteria[3], respectively. The TAPS (Toronto Activity Panel Survey) 2002-03 data set is used for this purpose. Specifically, the data were obtained from a Computerized Household Activity Scheduling Elicitor (CHASE) survey conducted in Toronto, Ontario. The data set contains 474 adults residing in 240 households. In total, these sampled adults undertook 28,680 uniquely labeled activities over the course of one week, each of which is associated with attributes[4].

Table 1 compares the number of joint episodes identified by different criteria. When using restrictive criteria (same time and same activity type/travel mode), only 1,795 joint activity and 470 joint travel episodes are found, compared to 8,055 and 737 episodes, respectively, when using flexible criteria. The occurrences of joint activities and joint trips when using flexible criteria account for 44.5% and 16.1% of total activity and trip episodes in the data set. Within this line of research, several studies have been conducted (Gliebe and Koppelman 2005; Singhi 2002; Vovsha et al. 2004). For example, applying restrictive criteria to a two-day travel diary collected in Seattle, Washington, Gliebe and Koppelman (2005) indicated that, out of 26,492 out-of-home episodes, 29% is identified as either joint activity and/or a shared ride by two adult householders. However, shared episodes between children and one adult household member were identified as independent due to their research purpose. Using the same criteria, Vovsha et al. (2004) reported that joint travel represents a significant percentage of total travel (limited to home-based motorized trips only), close to half of the mid-Ohio tours, and more than one-third of the New York

[3] A more detailed explanation about restrictive and flexible criteria can be found in the notation of Table 1.

[4] These include: 1) location: out-of-home activities, which represented 25.6% of the total activities, and in-home activities; 2) 67 specific activity types (e.g., housewares shopping, clothes shopping), which are summarized into 10 generic group labels (e.g., shopping); 3) 31 specific travel modes (e.g., SUV), categorized into 4 generic group types (e.g., automobile).

tours, about 75% of which is made by members of the same household. Here joint travel is measured at the tour level, which includes fully joint tours and partially joint tours (i.e., joint at one directional leg only). The work by Singhi (2001), to our knowledge, represented one of the early efforts to relax the joint-in-time criterion, by allowing for a 5-minute temporal gap for both starting times and ending times. It is reported that, in two German cities, Karlsruhe and Halle, 22% of the total trips undertaken by individuals within a household are joint. One thing that should be noted, however, is that values reported in the above studies are not comparable due to different units of analysis (i.e., episode vs. tour) and different research foci (i.e., adults only vs. all householders) across different regions.

We also calculated the proportion of joint activities that take place out-of-home. Out of all joint activities, 10.1% (815) occur outside the home when using the flexible criteria compared to 19.89% (357) when using the restrictive criteria. The proportion of out-of-home joint activities is much lower than that of in-home joint activities. Two reasons are suggested for this: one is that householders are more likely to participate in joint activities in the home; the other is related to the dominance of in-home activities collected in the original survey data set (74.4%).

<Insert Table 1>

Such numerical differences between restrictive and flexible criteria are also illustrated in Fig. 2, which displays how the spatio-temporal features of human activity/travel behavior are visualized in ArcScene. At the bottom of the figure, the black dots represent the participant household locations in Toronto, and grey lines represent the highway network. As an example, on the right side of the figure is the space-time path of a husband (the grey line) and a wife (the black line) on one particular day. The two attribute tables show records of joint episodes undertaken by the couple together, when using flexible criteria (above) and restrictive criteria (below), which are also, respectively, represented as straight lines with crosshairs, and bold black lines in this figure. From this figure, we find that, in the bottom right-hand corner, the two lines overlap each other, which means that this joint episode (i.e., night sleep at the beginning of the day) is effectively identified by both criteria. In the morning, the wife leaves for work, but the husband undertakes some recreational activities near the home and then picks up their children in the afternoon. After work, the wife drives to meet her husband at a friend's place and attend a social event together, which is the second joint activity identified for the couple using flexible criteria (see the upper table). This joint activity, along with six other episodes (i.e., meals, entertainment, and night sleep), is not identified by restrictive criteria (see the lower table).

<Insert Fig. 2>

The functions supported by the Space-Time Path Visualizer tool are not limited to illustrating the differences between flexible and restrictive criteria, however. The tool also aids in understanding human activity patterns in several ways. First, the tool, combined with some visualization functions offered by ArcScene (i.e., zooming in, zooming out, panning and rotating), provides a dynamic and interactive environment within which human activity/travel behavior patterns can be examined from different angles. For instance, the researcher can change the symbols of space-time paths (i.e., color and width), or query data (i.e., focusing only on sub-groups of the whole data set, such as females, retired persons, etc.), with the impacts of such changes being seen quite easily. This is more functional compared with the conventional representation approaches (e.g., 2D) described earlier. Second, by retaining the spatial and temporal characteristics of the original data, the Visualizer can be used to identify complex relationships (i.e., "bundles") among household members within the scope of human vision (Kwan 2000).

Table 2 describes the variation in several key attributes of joint and independent activities identified using restrictive and flexible criteria: frequency, starting time, ending time and duration (minutes). These attributes are selected for comparison because of their significant impacts on understanding urban activity-travel patterns, which has two implications. First, by accounting for joint out-of-home activities, predictions of activity-travel demand models are more likely to be accurate (Scott and Kanaroglou 2002). Second, attributes of independent and joint activities, such as timing and duration, are helpful to capture potential responses to certain operational strategies (e.g., advanced traffic control strategies), and evaluate the effectiveness of some transportation demand management (TDM) measures (e.g., congestion pricing) *(*Bhat and Steed 2002*)*. Recently, aware of these implications, some modeling efforts have focused on the timing (Arentze and Timmermans 2004) and duration of daily activities (Schwanen 2004). However, little research has been conducted in the context of independent/joint activities/travel.

Frequency is measured as the observed average number of individual/joint episodes undertaken by each household during the survey week. Starting/ending times are measured as the observed average starting/ending times for independent and joint episodes, respectively. All the above attributes are calculated for both flexible and restrictive criteria. However, in the case of flexible criteria, the starting/ending times are measured as the average starting/ending times of the overlapping time periods of joint episodes, which are the maximum starting time and minimum ending time reported by householders undertaking the same activity. From this table, we find that the frequency of joint episodes when using flexible criteria is much higher than that when using restrictive criteria, which is opposite for independent episodes. This is expected due to the ability of flexible criteria to identify more joint episodes than restrictive criteria. The flexible criteria report earlier starting time, ending time and shorter duration of joint episodes than restrictive criteria. For independent episodes, the flexible criteria report a later starting time, but earlier ending time and shorter duration values than the restrictive criteria.

Furthermore, to explore extensively the distribution patterns of starting/ending times, we examined some other statistical measures, including the median, skewness, and kurtosis.

The median, as a measure of central tendency, is not as sensitive to outlying values (i.e., extremely high or low values) as the mean, but shows a similar trend with it. A skewness value of zero represents a symmetric distribution (normal). The results indicate that, for both independent and joint episodes, the distributions of the starting and ending times when using flexible criteria are slightly less skewed than when using restrictive criteria, although each has a left tail (i.e., negative sign). Kurtosis is a measure of the extent to which observations cluster around a central point. Its value is 0 for a normal distribution, while a negative value indicates the observations cluster less and have shorter tails. For joint episodes, the Kurtosis statistics indicates that the starting and ending times by flexible criteria are less clustered than those by restrictive criteria, a trend which is converse for independent episodes.

<Insert Table 2>

Fig. 3 presents the different compositions of joint activities in terms of their purposes based on different criteria. We find that for both criteria, similarly, the role of night sleep is predominant (45.7% when using flexible criteria vs. 44.1% when using restrictive criteria) over other activity types. However, compared with flexible criteria, restrictive criteria report a larger proportion of meals, but lower proportions of household obligations and entertainment. One possible reason for this disparity is that people tend to report certain types of joint activities (i.e., meals) more consistently than others (i.e., watching TV, email, relaxing, etc.). The proportions of other seven activity types remain at around the same level for both criteria.

<Insert Fig. 3>

7. Conclusions

As argued at the beginning of this paper, recognition of the importance of intra-household interactions has recently produced a growing body of research, aiming to enhance our understanding about this phenomenon. Several issues, however, have not been well addressed by those studies. First, the widely used method to identify joint episodes by requiring the same purpose (activity type), exact location, timing and duration might be too restrictive to include all occurrences of joint episodes. The second issue is the visualization of intra-household interactions in 3D. Previous research efforts, at most, displayed co-located activities in space and time (e.g., Buliung and Kanaroglou 2006;Yu 2006), which cannot be referred to as joint activities due to lack of a third dimensional criterion – for example, activity type (Buliung and Kanaroglou 2006).

Our research moves beyond past studies of exploring intra-household interactions by developing the first household-based, spatio-temporal GIS toolkit, which is implemented in the environment of ArcGIS 9.1. This toolkit includes two tools, namely, the Space-Time Coincidence Analyst tool and the Space-Time Path Visualizer tool, which are complimentary, but independent. In other words, the two tools, collectively, support functions including the identification of joint episodes, the representation of space-time paths, and spatio-temporal relationships of these paths in 3D, or they can be used independently, depending on the user's purpose. Furthermore, the toolkit can be applied to any household-based, activity/travel data set so long as required information is specified by the user.

Our toolkit also allows a comparison of important attributes of joint and independent activities between restrictive and flexible criteria. Those key attributes include frequency, timing, duration and composition of activity purposes. Our empirical study, which applies the toolkit to the TAPS (Toronto Activity Panel Survey) 2002-03 data set, suggests that considerable variation exists in the number of joint activity/travel episodes identified using different classification criteria. Specifically, when using restrictive criteria (i.e., same timing, specific activity type/travel mode), only 2,265 joint activity/travel episodes are identified compared to 8,792 when using more flexible criteria. In turn, our results show that certain key attributes for independent and joint activity/travel episodes (i.e., frequency per household, starting time, ending time and duration) also vary under the different classification criteria. We also compared the composition of joint episodes when using different criteria, which has direct implications for how to improve designs of future activity/travel surveys.

The design presented in this paper provides a useful toolkit for exploring comprehensively intra-household interactions. However, one limitation is that only intra-household interactions between any two household members can be captured by this framework. Although it sounds workable in theory, complexity increases exponentially when extending our toolkit from the two-person dimension to three or more-person dimensions. At the same time, however, this limitation can be easily overcome by the researcher through follow-ups. For instance, if the researcher is interested in joint episodes undertaken by three family members, a simple query (i.e., *JTOT_01=1 and TOT_02=1*) can be built easily and quickly either in ArcGIS or Microsoft Access. Another limitation is that we have not applied our toolkit to other data sets, which might exhibit some slightly different results, although similar trends are expected. In general, we suggest that conclusions should not be derived from this study without first considering these limitations.

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About the authors

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Table 1 Comparison of the number of joint episodes using different criteria

	Type/mode[1]	Same time	Flexible time[2]	Difference
Joint activity	Specific	1,795 (357)[3]	6,599 (787)	4,804 (430)
	Generic	1,848 (359)	8,055 (815)	6,207(456)
	Difference	53 (2)	1,456 (28)	
Joint travel	Specific	470	721	251
	Generic	474	736	262
	Difference	4	15	

[1] Specific type/mode refers to the most disaggregated activity type/travel mode, while generic type/mode refers to a more aggregated activity type/travel mode. For instance, in our empirical study, the specific classification scheme includes 67 activity types and 32 travel modes, and the generic scheme includes 10 activity types and 4 travel modes.
[2] Flexible time for joint activity requires that the starting time of one activity is earlier than the ending time of the same activity undertaken by another person. Flexible time for joint travel allows for a 10-minute difference in the starting time and a 10-minute difference in the ending time reported by different individuals.
[3] () represents the number of out-of-home activities when using different criteria.

Table 2 Comparison of key attributes of joint vs. individual episodes using flexible and restrictive criteria

Type	Criteria	Frequency per household	Starting time (minutes)				Ending time (minutes)				Duration (minutes)
		Mean	Mean	Median	Skewness	Kurtosis	Mean	Median	Skewness	Kurtosis	Mean
Joint episodes	Flexible	31.4	795.3	960	-0.42	-1.26	916.1	1050	-0.20	-1.50	120.7
	Restrictive	7.4	812.9	1020	-0.53	-1.10	945.1	1080	-0.25	-1.46	132.3
Independent episodes	Flexible	88.1	816	840	-0.37	-0.65	923.1	960	-0.25	-0.93	107
	Restrictive	112.1	807.9	845	-0.42	-0.77	924.5	985	-0.23	-1.09	116.5

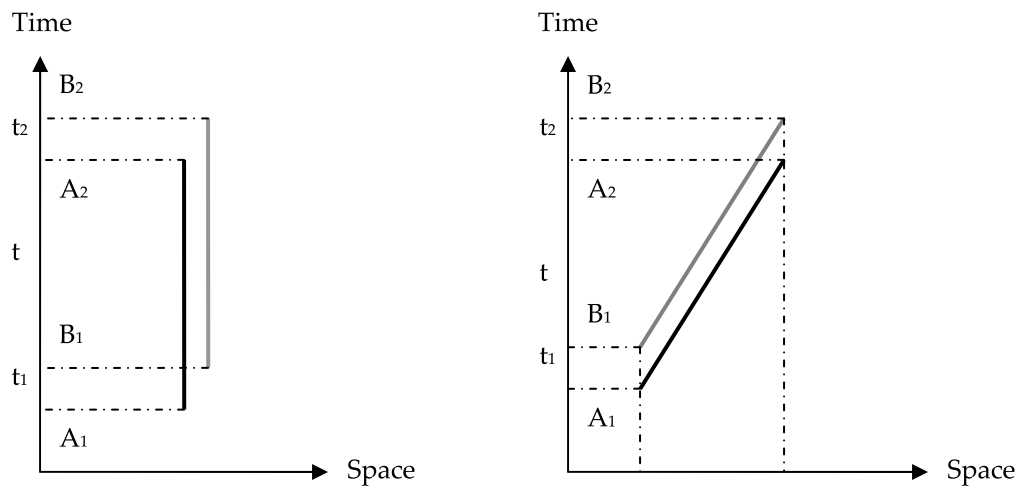

Fig. 1 a) Joint activity episode; b) Joint travel episode

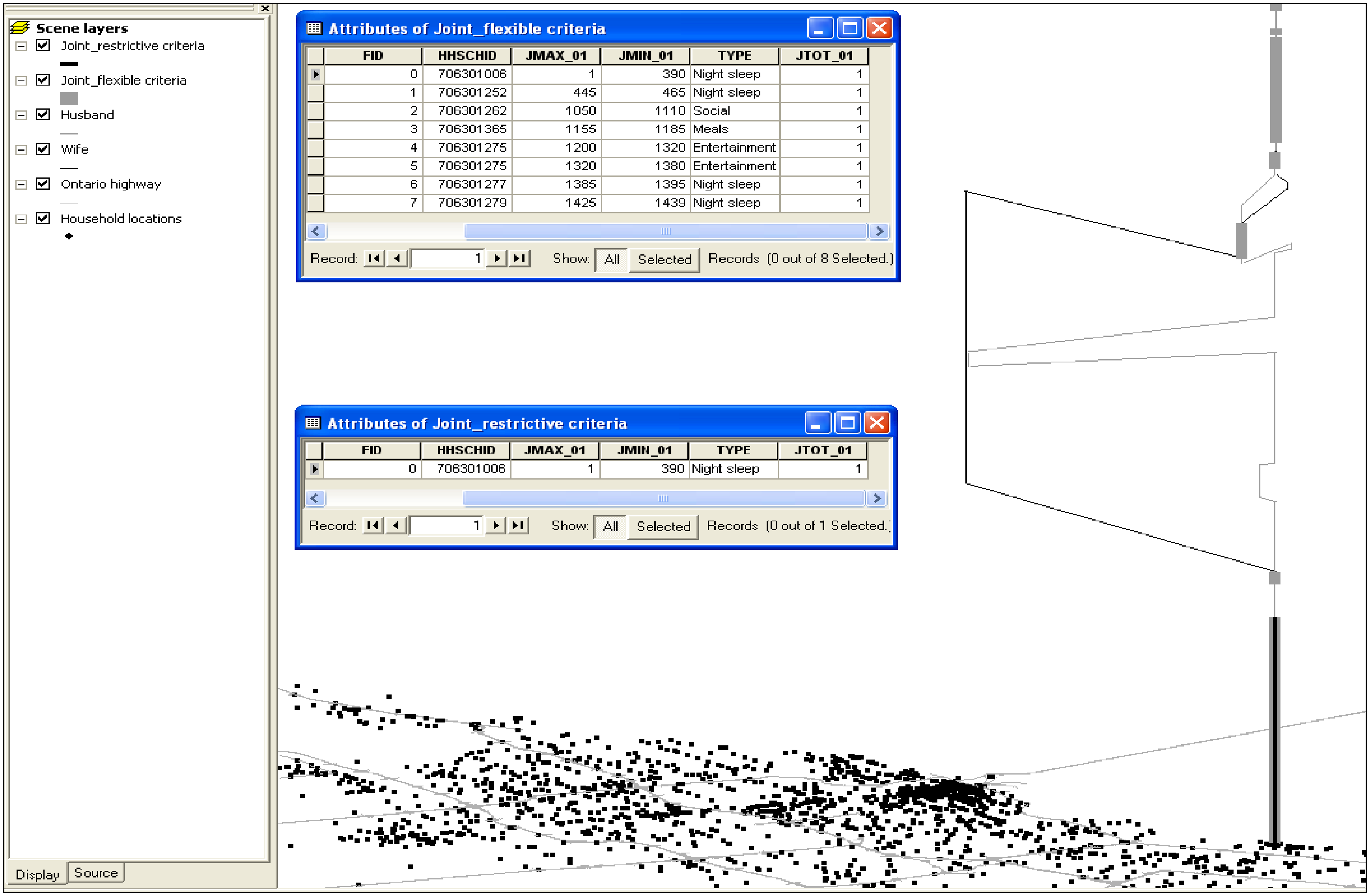

Fig. 2 Visualization of two space-time paths using the Space-Time Path Visualizer Tool in ArcScene

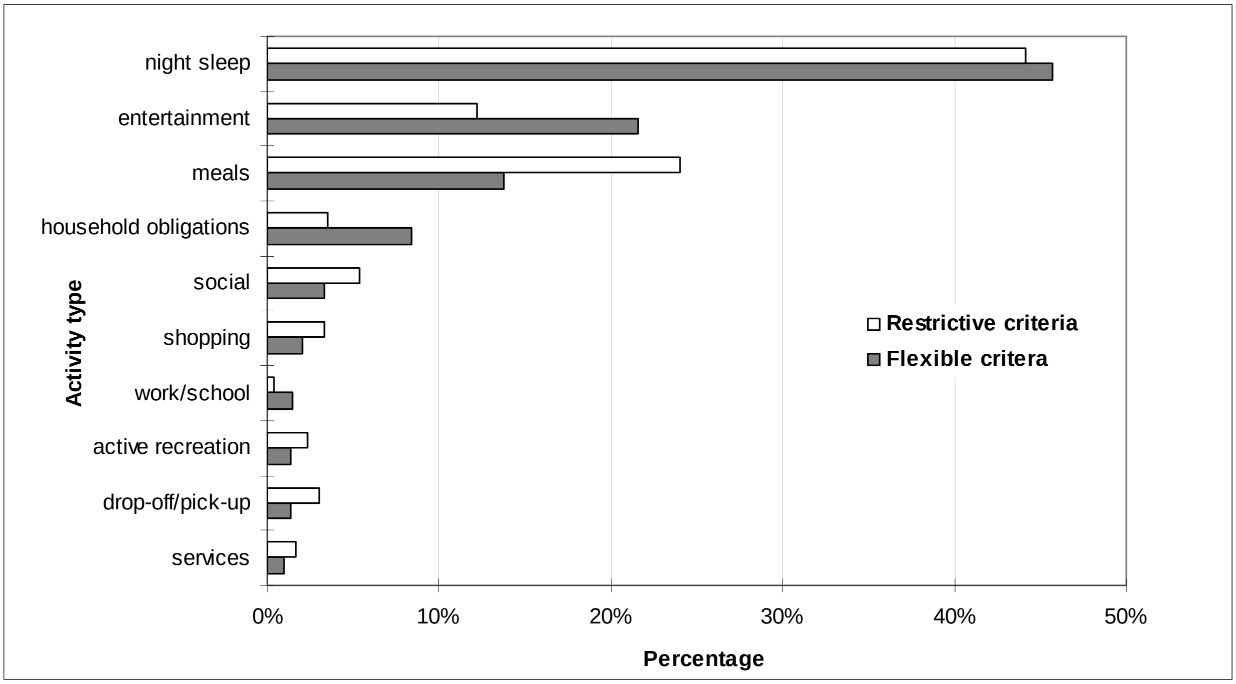

Fig. 3 Comparison of the activity type composition of joint activity episodes using flexible criteria and restrictive criteria, respectively

Appendix

Components of the Space-Time Coincidence Analyst tool

ImportFile serves to prepare data for analysis, which asks the user to locate required fields of a survey file. Such a design reflects the flexibility of our tool, which can be applied to most surveys, as long as necessary information is input. Since our toolkit is designed for the exploration of intra-household interactions, the following basic information is required: 1) IDs, which include Household ID, Member ID and Activity/Travel ID; 2) household characteristics, collecting information such as the number of adults and children in each household as well as the gender of each household head; and 3) episode table, which stores some basic information about each episode (activity/travel) recorded in the survey data set. This includes the location (*xy* coordinates), timing (starting/ending times), episode type, travel mode and the time frame of the survey. As long as the above information is identified, the analyst tool can be used for various household surveys (i.e., one-day or multiple-day) from different regions, except for those focusing only on one household member. The reason for this is that the tool is designed specifically to explore intra-household interactions. Once the survey file is imported, the next step is to classify joint activities and travel. Through this step, newly created variables are attached to the original survey data, indicating whether each episode is undertaken by two householders together or independently, by using both flexible and restrictive criteria, respectively[5]. Therefore, our toolkit can be used to compare results arising from these two sets of criteria. Also, for joint activities, the exact joint time period is calculated and appended to the output files for any two household members. The next step called "Join" appends these indicators to the original survey data set. To facilitate exploration, we also designed a "Query" interface to meet particular requirements by the user, who may want to focus on certain household types (i.e., single with children, couple without children, and couple with children). Once a certain type is chosen, the "Next" button brings the user to the corresponding user-friendly interface. For each query, the output is saved as a database file into a directory designated by the user.

[5] For example, if there are three members within one household (persons 0, 1 and 2), three new variables are added, which are JTOT_01 (indicating whether person 0 and 1 are undertaking activities together), JTOT_02 (indicating whether person 0 and 2 are undertaking activities together) and JTOT_12 (indicating whether person 1 and 2 are undertaking activities together). At the same time, three other fields (JSTOT_01, JSTOT_02, and JSTOT_12) are created, which indicate whether an episode is joint or independent, but based on restrictive criteria instead. Similarly, all the above indicators are generated for traveling.

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