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Clustering Daily Patterns of Human Activities in the City

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Abstract Data mining and statistical learning techniques are powerful analysis tools yet to be incorporated in the domain of urban studies and transportation research. In this work, we analyze an activity-based travel survey conducted in the Chicago metropolitan area over a demographic representative sample of its population. Detailed data on activities by time of day were collected from more than 30,000 individuals (and 10,552 households) who participated in a 1-day or 2-day survey implemented from January 2007 to February 2008. We examine this large-scale longitudinal data in order to explore three critical issues: (1) the inherent daily activity structure of individuals in a metropolitan area, (2) the variation of individual daily activities—how they grow and fade over time, and (3) clusters of individual behaviors and the revelation of their related socio-demographic information. We find that the population can be clustered into 8 and 7 representative groups according to their activities during weekdays and weekends, respectively. Our results enrich the traditional divisions consisting of only three groups (workers, students and non-workers) and provide clusters based on activities of different time of day. The generated clusters combined with social demographic information provide a new perspective for urban and transportation planning as well as for emergency response and spreading dynamics, by addressing when, where, and how individuals interact with places in metropolitan areas.

Keywords: *Human Activity, Eigen Decomposition, Daily Activity Clustering, Metropolitan Area, Statistical Learning*

1 Introduction

Considerable efforts have been put into understanding the dynamics and the complexity of cities (Reggiani and Nijkamp 2009). To our advantage, in general, individuals exhibit regular yet rich dynamics in their social and physical lives. This field of study was mostly the territory of urban planners and social scientists alone, but has recently attracted a more diverse body of researchers from computer science and complex systems as a result of the advantages of interdisciplinary approaches and rapid technology innovations (Foth et al. 2012). Emerging urban sensing data such as massive mobile phone data, and online user-generated social media data, both in the physical and virtual world (Crane and Sornette 2008; Kim et al. 2006), has been accompanied by the development of data mining and statistical learning techniques (Kargupta and Han 2009) and an increasing and more affordable computational power. As a consequence, one of the fundamental and traditional questions in the social sciences, “*how human allocate time to different activities as part of a spatial, temporal socio-economic system,*” becomes treatable within an interdisciplinary domain. By clustering individuals according to their daily activities, our ultimate goal is to provide a clear picture of how groups of individuals interact with different places at different time of day in the city.

The advances of our study lie in two folds. First, we do not superimpose any predefined social demographic classification on the observations, but use the presented methodology to cluster the individuals. This provides an advantage over traditional human activity studies, which tend to ignore individuals’ temporal activity differences (Hanson and Kwan 2008), and treat metropolitan residents either as more homogeneous groups or pre-specified subgroups differentiated by social characteristics (Handy 1993; Shen 1998; Sang et al. 2011; Kwan 1999). We let the inherent activity structure inform us of the patterns in order to generate the clusters of daily activities in a metropolitan area. Second, compared with recent studies on human mobility and dynamics employing large-scale objective data such as mobile phone or GPS traces of individual trajectories (Wang et al. 2011a; Song et al. 2010; Gonzalez et al. 2008; Candia et al. 2008), we linked in the usually absent rich information regarding activity categories and social demographics of individuals. By summarizing the socio-demographic characteristics of each cluster, we try to reveal the social connections and differences within and among each activity cluster. The scope of our results can be applied to inform diverse areas that are concerned by models of human activity such as: time-use studies, human dynamics and mobility analysis, emergency response or epidemic spreading. We hope that this work connects with researchers in urban studies, computer sciences and complex systems, as a case of study of how interdisciplinary research across these fields can produce useful pieces of information to understand city dynamics.

1 The rest of the paper is organized as follows. In Section 2 we survey the
2 literature of related studies. Section 3 describes the data that we are using in this
3 study, and our data processing methodology. In Section 4, we provide the
4 mathematical framework and justify the selected methods of analysis, including
5 the principle component analysis (PCA) to extract the primary eigen activities, the
6 *K*-means clustering algorithm, and the cluster validity measurement that we
7 propose to use to identify the number of clusters. We present our findings on the
8 eigen activities, clustering of daily activity patterns, and their associated socio-
9 demographic characteristics in Section 5, and conclude our study and summarize
10 its significance and applications for future work in Section 6.

15 2 Background and Related Work

18 Different facets of spatiotemporal characteristics of human activities have long
19 been studied by researchers in sociology (Geerken et al. 1983), psychology (Freud
20 1953; Maslow and Frager 1987), geography (Hägerstrand 1989; Yu and Shaw
21 2008; Harvey and Taylor 2000; Hanson and Hanson 1980), economics (Becker
22 1991), and urban and transportation planning (Chapin 1974; Bhat and Koppelman
23 1999). Nowadays, studies in these fields can benefit from recent innovation in
24 both data sources and analytical approaches, which have inspired a new
25 generation of studies about the dynamics of human activities. For example,
26 Gonzalez et al. (2008) studied the trajectories of 100,000 anonymized mobile
27 phone users, and showed a high degree of spatial regularity of human travels.
28 Eagle and Pentland (2009) analyzed continuous mobile phone logging locations
29 collected from an experiment at MIT, studied the behavioral structure of the daily
30 routine of the students, and explored individual community affiliations based on
31 some a priori information of the subjects. Song et al. (2010) measured the entropy
32 of individuals' trajectory using mobile phone data, and found high predictability
33 and regularity of users' daily mobility. Wang et al. (2011a) tracked trajectories and
34 communication records of 6 million mobile phone users, and examined how
35 individual mobility patterns shape and impact their social network connections.

36 Due to privacy and legal constraints, these kinds of studies generally face
37 challenges in depicting a whole picture that connects behavior with social,
38 demographic and economic characteristics of the studied subjects. While the new
39 datasets allow us to study massive aggregated travel behavior and social
40 interactions, they have limited capacity in revealing the underlying reasons
41 driving human behavior (Nature Editorial 2008). In order to have details, usually
42 we must limit group sizes. For example, Eagle et al. (2009) used the Reality
43 Mining data to infer friendship network structure. The data mining technique of
44 this study is very promising but, without socioeconomic information, it is hard for
45 researchers to further explore the determining factors beneath the network,
46 especially when the constraint imposed on a specific community (such as
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1 university campus), and the scale are enlarged to include entire metropolitan area
2 and beyond.

3
4 Meanwhile, technology development in geographic information systems
5 (GIS) such as automated address matching, and in computer-aided self-interview
6 (CASI) enable us to have higher spatial and temporal resolution than in the past,
7 which leads to improvements in the accuracy, quality and reliability of the self-
8 reported survey data (Axhausen et al. 2002; Greaves 2004). Compared with urban
9 sensing data (such as mobile phone data), survey data is disadvantaged by high
10 cost, low frequency, and small sample size. However, in terms of the richness of
11 socioeconomic and demographic information, survey data provides much richer
12 information for exploring social differences underlying the human activity
13 dynamics, and thus enables us to develop more nuanced models for explaining
14 and predicting human activity patterns.

15
16 Inspired by many of the aforementioned issues and studies, in this paper,
17 we exploit the richness of survey data using data mining techniques, which have
18 not been applied in this context before. Since the survey collected over the
19 metropolitan area is conducted by the metropolitan planning organization (MPO)
20 for regional transportation planning purposes, it is free for public access, reliable,
21 and representative of the total regional population. Daily activities of groups of
22 individuals in cities should have underlying structures which can be extracted
23 using data mining techniques similar to the ones applied nowadays to clustering
24 users' on-line behavior (Yang and Leskovec 2011). To those means, in this work
25 we show that the PCA/eigen decomposition method (Turk and Pentland 1991) and
26 *K*-means clustering algorithm (Ding and He 2004) are appropriate to analyze
27 urban survey data. These techniques are successfully applied to reconstruct the
28 original data sets and obtain meaningful clusters of individuals. We provide a
29 rich, yet simple enough, set of activity clusters, with additional time-of-day
30 information, which go beyond the traditional simply defined groups and can be
31 adopted by current urban simulators (Waddell 2002; Balmer et al. 1985; Bekhor et
32 al. 2011). The kind of analyses presented here is also useful to compare and
33 understand the dynamics of different cities.

3 Data

34
35 In this section, we describe the activity survey data in the Chicago metropolitan
36 region and our techniques for processing the data. From the survey data, we derive
37 two separated sample sets (i.e., for an average weekday and weekend). For each of
38 the sets we know detailed information about individuals' daily activity sequences,
39 and their social demographics. For simplicity reasons, we aggregate the 23 self-
40 reported primary activities into 9 major activities. We divide the 24 hours into 288
41 five-minute intervals for further data analysis.

42
43 The data used in this study are from a publicly available "Travel Tracker
44 Survey" —a comprehensive travel and activity survey for Northeastern Illinois

designed and conducted for regional travel demand modeling (Chicago Metropolitan Agency for Planning 2008). Due to its purpose, the sampling framework of the survey is a stratification and distribution of surveyed household population in the 8 counties of the Northeastern Illinois Region. It closely matches the 2000 US Census data for the region at the county level. The data collection was implemented between January 2007 and February 2008, including a total of 10,552 households (32,366 individuals). Every member of these households participated in either a 1-day or 2-day survey, reporting their detailed travel and activity information starting from 3:00 a.m. in the early morning on the assigned travel day(s). The survey was distributed during 6 days per week (from Sunday to Friday) in the data collection period. Among panels of the publicly available data, in this study, we focus on those containing information about households (e.g., household size, income level), personal social demographics (e.g., age, gender, employment status, work schedule flexibility), trip details (travel day, travel purpose, arrival and departure times, unique place identifiers), and location.

3.1 Data Processing

In the original trip data, location is anonymized by moving the latitude and longitude of each location to the centroid of the associated census tracts. By assuming that people move from point A to point B in a straight line with constant moving speed, we are able to fill in the latitude and longitude locations of the movement between two consecutive destinations. Using this method, we reconstruct the data at a 1-minute interval, providing a time stamp (in minutes), a location with paired latitude and longitude, an activity type, and a unique person-day ID. In order to reduce the high dimension of the 23 primary purposes in the original survey data, we aggregate them into 9 activity types as shown in Table 1. We also use a specific color for each activity throughout the entire paper.

Table 1 Newly aggregated 9 activity types v.s. the original 23 primary trip purposes

| Aggregated Activity Types | Original Primary Trip Purposes |
|----------------------------|---|
| Home | 1. Working at home (for pay); 2. All other home activities |
| Work | 3. Work/Job; 4. All other activities at work; 11. Work/Business related |
| School | 5. Attending class; 6. All other activities at school |
| Transportation Transitions | 7. Change type of transportation/transfer; 8. Dropped off passenger from car; 9. Picked up passenger; 10. Other, specify-transportation; 12. Service private vehicle; 24. Loop trip |
| Shopping/Errands | 13. Routine shopping; 14. Shopping for major purchases; 15. household errands |
| Personal Business | 16. Personal Business; 18. Health Care |
| Recreation/Entertainment | 17. Eat meal outside of home; 20. Recreation/Entertainment; 21. Visit friends/Relatives |
| Civic/Religious | 19. Civic/Religious activities |
| Other | 97. Other |

We label the activity type of individuals while traveling to be that of their destination activity type. For example, if an individual starts her morning trip from home to work at 7:00 a.m., arrives at her work place at 7:30 a.m., and begins work from 7:31 a.m. and finishes work at 11:30 a.m., we label her activity type during the time period [7:00 a.m., 11:30 a.m.] as "work".

3.2 Human Daily Activities on Weekdays and Weekends

We generate a separate animation visualizing the movement and activities (differentiated by nine colors demonstrated in Table 1) of the surveyed individuals in the Chicago metropolitan area for an average weekday and weekend. Since the public location data for each destination that an individual visited is anonymized by the centroid of the census tract, for visualization purposes, we differentiate destinations by adding a very small random factor (see Figures 1 and 2).

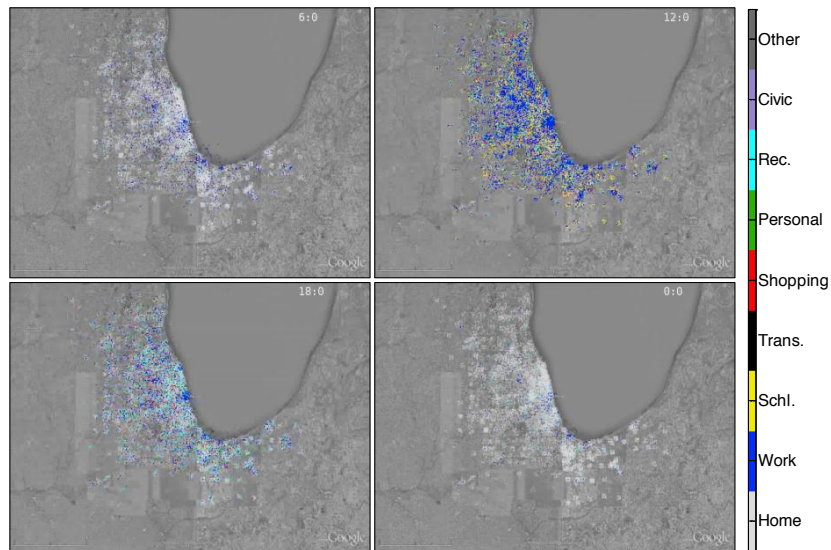


Figure 1 Snapshots of human activities at different times-of-day on a weekday in Chicago

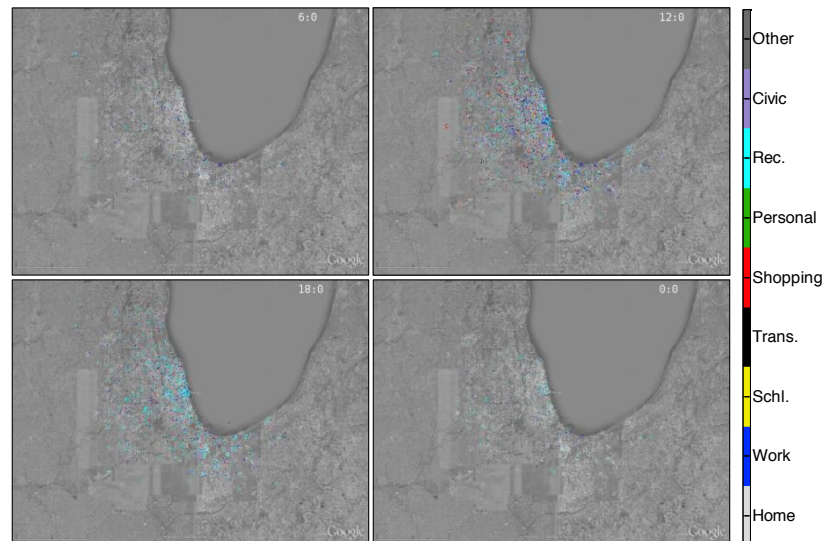


Figure 2 Snapshots of human activities at different times-of-day on a weekend in Chicago

An Average Weekday

We use the first-day sample of the 1-day survey distributed from Monday to Thursday, plus the second-day sample of the 2-day survey distributed on Sunday as an average weekday sample. We get a total of 23,527 distinct individuals who recorded their travel and activities during any day (starting from 3:00 a.m. on Day 1, and ending at 2:59 a.m. on Day 2) between Monday and Thursday. We exclude surveys on Fridays on purpose, because as confirmed from our analysis, with Friday approaching to the weekend, patterns of human activities on that day usually differ from those during the rest of the weekdays. [Figure 1](#) shows four snapshots of the animation of movement and human activities in the Chicago metropolitan area that we generated for an average weekday. The top row shows snapshots at 6:00 a.m. and 12:00 p.m., and the bottom pair are those at 6:00 p.m. and 12:00 a.m. We can see that in the early morning, the majority of people are at home while some have already started work. At noon time, a large percent of people are at work or at school, with some groups of people doing shopping, recreation, and personal businesses. In the early evening, some people are out for recreation or entertainment and some are already at home. At midnight, most people are at home, and only a few are out for recreation, or still at work place.

An Average Weekend

For an average weekend (Saturday or Sunday), we get a smaller sample compared to that of weekday, totaling of 5,481 distinct individuals. We can see that the activity patterns of a weekend are very different from those during weekdays (see [Figure 2](#)). During the early morning, majority of the people are at home while a few are out for recreation or still at work. At noon time, many people have been out for recreation/entertainment, shopping or civic (religious) activities, and some are staying at home and a small proportion people are at work. In the early evening, the majority people who are not at home are doing recreation or entertainment, while some are doing shopping. At midnight, while most people are at home, a few are out for recreation/entertainment, mostly concentrated in the downtown area.

Individual and Aggregated Daily Activity Variations

Figures 1 and 2 provide us with a sensible landscape about individual's daily activities in the metropolitan area. Nevertheless, we need additional tools to analyze the composition of individuals conducting different activities over time. By exhibiting the activity-type change along the time axis for every individual in the sample, we are able to retain rich information about individual activity variation at different time of day. In [Figure 3](#), we depict respectively, for an average weekday and weekend, the 24-hour human activity variations (using the corresponding colors defined in Table 1) in Chicago. The x axis represents time-of-day (starting from 3:00 a.m. of Day 1 and ending at 2:59 a.m. on Day 2); and

the y axis displays all samples (i.e., each line parallel to the x axis represents an individual sample). By summing up the total number of individuals conducting different types of activities along the 24-hours of the weekday and weekend, we are able to generate [Figure 4](#) which reveals the aggregated temporal variation of human activities in Chicago. In addition, each inset figure zooms in on the detailed information of the less-major activities (i.e., those with a smaller share of total volume) over time.

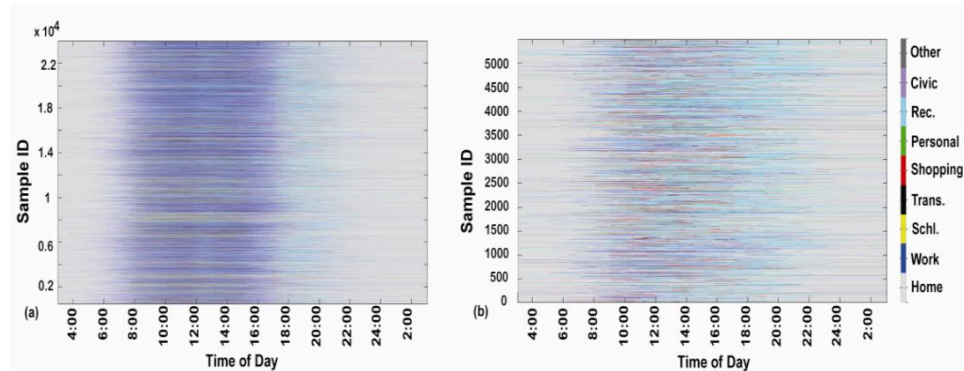


Figure 3 Individual daily activities on a (a) weekday and (b) weekend in Chicago

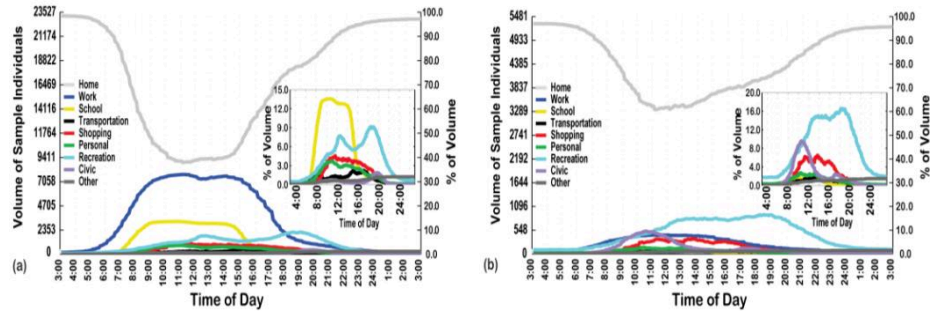


Figure 4 Temporal rhythm of human activities on a (a) weekday and (b) weekend in Chicago

3.3 Data Transformation

We divide the 24 hours in a day into five-minute intervals and use the activity in the first minute of every time interval to represent an individual's activity during that five-minute period. During each five-minute interval, an individual is labeled with one of the nine activities (defined as in Table 1). We then use a sequence of 288 zeros or ones (=24 hours x 12 five-minute intervals per hour) to indicate whether the individual is engaged in each particular activity during each interval. In [Figure 5](#), a "one" (meaning 'yes') is marked black while "zero" is white. For each sampled individual, the 9 activities and 288 time steps result in a sequence of 2,592 black/white dots along one row. Each of the 23,527 sampled individuals generates a row that is stacked along the y -axis.

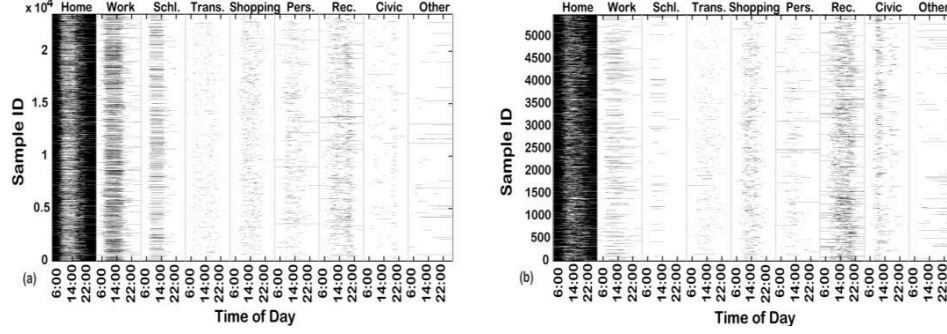


Figure 5 Data transformation of individual activities on a (a) weekday and (b) weekend in Chicago

4 Mathematical Framework and Methods

We employ two methods, namely, the principal component analysis/eigen decomposition and the K -means clustering algorithm, to answer the two questions raised earlier in this paper: (1) discovering the inherent daily activity structure of individuals in the metropolitan area; and (2) clustering individuals in the metropolitan area based on dissimilarity of their daily activities.

4.1 The Setting

During any of the 288 five-minute time intervals, an individual must conduct one of the nine activities defined in Table 1. For $(a_1, \dots, a_m)' \in \{0,1\}^m \subset \mathbb{R}^m$, $m = 2,592$, we say that $(a_1, \dots, a_m)'$ satisfies the *compatibility condition*, if for any $t = 1, 2, \dots, 288$, $\sum_{l=1}^9 a_{t+288 \times (l-1)} = 1$. We define the *space of individuals' daily activity sequence*, \mathcal{S} , as follows:

$$\mathcal{S} \triangleq \left\{ \begin{pmatrix} a_1 \\ \vdots \\ a_m \end{pmatrix} \in \{0,1\}^m \subset \mathbb{R}^m \mid \begin{pmatrix} a_1 \\ \vdots \\ a_m \end{pmatrix} \text{ satisfies compatibility condition} \right\}.$$

In this study, the population is the set of individuals in the Chicago metropolitan area. For simplicity, we identify the sample space Ω as the population. As we study the average weekday and weekend separately, we have two cases. For the weekday case, an individual's daily activity sequence can be described by the following random vector:

$$\mathbf{A}_D: \Omega \rightarrow \mathcal{S} \\ \omega \mapsto \begin{pmatrix} A_{D1}(\omega) \\ \vdots \\ A_{Dm}(\omega) \end{pmatrix}.$$

where for $j = t + 288 \times (l - 1)$, $t \in \{1, \dots, 288\}$ and $l \in \{1, \dots, 9\}$, $A_{Dj}(\omega) = 0$ or 1, depending on if the individual ω is conducting activity l in time interval t on the weekday. We can define the random vector \mathbf{A}_E for the weekend case similarly.

From the survey data, we get n random samples $(\mathbf{a}_{D,i}, \mathbf{a}_{E,i}, \mathbf{b}_i)$, $i = 1, \dots, n$, where \mathbf{b}_i stands for individual i 's social demographic information such as age, gender, employment status, work schedule, etc. Note that for a sample individual i , we may only observe $\mathbf{a}_{D,i}$ (i.e. we do not have information on his/her weekend activity) as explained in the data description section. Let \mathcal{O}_D and \mathcal{O}_E denote the

sets of samples where $\mathbf{a}_{D,i}$ and $\mathbf{a}_{E,i}$ are observed, respectively. For the weekday (weekend) case, we focus on set \mathcal{O}_D (\mathcal{O}_E), and renumber the samples in \mathcal{O}_D (\mathcal{O}_E) from 1 to n_D (n_E), where $n_D = 23,527$ ($n_E = 5,481$). As the analytical approaches for the weekday and weekend are the same, henceforth we use the weekday case as an illustration, in which we have observations $(\mathbf{a}_i, \mathbf{b}_i)$, $i = 1, \dots, n$, where $\mathbf{a}_i = (a_1, \dots, a_m)' \in \mathcal{S}$. We omit the subscript "D" in notations for simplicity when there is no ambiguity.

4.2 Principal Component Analysis/Eigen Decomposition

Principal component analysis (PCA) and eigen decomposition are closely related as principal components are obtained from the eigen decomposition of the population/sample covariance matrix (Hastie et al. 2009). We present the sample version here, and the population version is similar. For each sample individual i , let \mathbf{d}_i denote the deviation from the mean, i.e., $\mathbf{d}_i = \mathbf{a}_i - \bar{\mathbf{a}}$, where $\bar{\mathbf{a}} = \frac{1}{n} \sum_{i=1}^n \mathbf{a}_i$ is the sample mean. Therefore the sample covariance matrix is given by $\mathbf{C} = \frac{1}{n-1} \sum_{i=1}^n \mathbf{d}_i \mathbf{d}_i' = \frac{1}{n-1} \mathbf{D} \mathbf{D}'$, where $\mathbf{D} = [\mathbf{d}_1, \dots, \mathbf{d}_n]$.

Eigenactivities

We know that \mathbf{C} is a positive semi-definite matrix, which is diagonalizable. So all the eigenvalues of \mathbf{C} are nonnegative. Let $\mathbf{V}' \mathbf{C} \mathbf{V} = \mathbf{\Lambda}$, where $\mathbf{\Lambda} = \text{diag}\{\lambda_1, \dots, \lambda_m\}$, and $\mathbf{V} = [\mathbf{v}_1, \dots, \mathbf{v}_m]$ is an orthogonal matrix whose j -th column \mathbf{v}_j is the eigenvector corresponding to λ_j . For convenience, we arrange the eigenvalues in descending order, i.e., $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_m \geq 0$. We call eigenvector \mathbf{v}_j the j -th *eigenactivity*.

Projection onto Eigenactivities

As $\{\mathbf{v}_1, \dots, \mathbf{v}_m\}$ forms an orthonormal basis for \mathbb{R}^m , \mathbf{V} becomes the corresponding change of coordinate matrix. Namely, given a vector $\mathbf{v} \in \mathbb{R}^m$ whose coordinate with respect to the natural basis is $\mathbf{x} = (x_1, \dots, x_m)'$, the corresponding $\{\mathbf{v}_1, \dots, \mathbf{v}_m\}$ -coordinate $\mathbf{y} = (y_1, \dots, y_m)'$ will be given by $\mathbf{y} = \mathbf{V}' \mathbf{x}$. When $\mathbf{v} = \mathbf{d}_i$ for a sample individual i , we call y_j ($j = 1, \dots, m$) the *projection of \mathbf{d}_i onto the j -th eigenactivity*, which is the projection of \mathbf{d}_i onto the j -th eigenactivity.¹

Activity Reconstruction

¹ We can also consider the *projection* of the random vector \mathbf{A}_D onto the j -th eigenactivity. Namely, let $\mathbf{Y}(\omega) = (Y_1(\omega), \dots, Y_m(\omega))' = \mathbf{V}' \cdot (A_{D1}(\omega), \dots, A_{Dm}(\omega))'$, then Y_j ($j = 1, \dots, m$) is called the *j -th principal component (of the population)*, which is the *projection of \mathbf{A}_D onto the j -th eigenactivity*. By the Strong Law of Large Numbers (SLLN), we can show that $\text{Cov}(Y_i, Y_j) \rightarrow 0$ almost surely as $n \rightarrow \infty$. For detailed discussion about SLLN, readers may refer to Durrett (2005). In this study, the sample sizes are large ($n_D = 23,527$ and $n_E = 5,481$), so the principal components are uncorrelated with each other. Note that in this study we do not use the principal components (Y_j), but the projections of \mathbf{d}_i onto the j -th eigenactivity (y_j).

Having known the eigenactivities and the corresponding projections of an individual i 's daily activity deviation from the mean, we can reconstruct the individual's daily activity sequence \mathbf{a}_i , by using a subset of eigenactivities. Suppose the projection of \mathbf{d}_i onto the first h eigenactivities are $(y_1, \dots, y_h)'$, then we obtain a vector $\mathbf{w} = (w_1, \dots, w_m)' \in \mathbb{R}^m$ according to formula $\mathbf{w} = \bar{\mathbf{a}} + (\mathbf{v}_1, \dots, \mathbf{v}_h)(y_1, \dots, y_h)'$. We use the following algorithm to reconstruct an individual's daily activity sequence as $\hat{\mathbf{a}}_i = (\hat{a}_1, \dots, \hat{a}_m)' \in \mathcal{S}$.

- Given any $t \in \{1, 2, \dots, 288\}$, let $M_t = \max\{w_t, w_{t+288}, \dots, w_{t+288 \times 8}\}$.
- Define $\mathbf{u}_t = (u_{t1}, \dots, u_{t9})' \in \{0, 1\}^9$ so that $u_{tl} = 1$ if and only if $w_{t+288 \times (l-1)} = M_t$.²
- So we get a 9-dimensional vector $\mathbf{u}_t \in \{0, 1\}^9$ that has one entry of 1, and we let $(\hat{a}_t, \hat{a}_{t+288}, \dots, \hat{a}_{t+288 \times 8}) = \mathbf{u}_t'$. It turns out that the reconstructed $\hat{\mathbf{a}}_i$ satisfies the desirable relation $\hat{\mathbf{a}}_i = \arg \min_{\mathbf{s} \in \mathcal{S}} \|\mathbf{s} - \mathbf{w}\|$.

The Appropriate Number of Eigenactivities

To answer the question "how many eigenactivities sufficient to rebuild the original daily activity structure", we define the reconstruction error $e(\mathbf{a}_i)$ for \mathbf{a}_i as the ratio of the number of incorrectly reconstructed entries to the total number of entries, i.e., $e(\mathbf{a}_i) = \frac{\|\mathbf{a}_i - \hat{\mathbf{a}}_i\|^2}{2592}$. Given any $\varepsilon > 0$, it is clear that we can find some $h > 0$, so that the average reconstruction error caused by ignoring the projections onto the ignored eigenactivities $\{\mathbf{v}_{h+1}, \dots, \mathbf{v}_m\}$ is no greater than ε . Let $\varepsilon_0 > 0$ be the acceptable error level, and define $h(\varepsilon_0)$ to be the smallest h such that the average reconstruction error, $\frac{\sum_{i=1}^n e(\mathbf{a}_i)}{n}$, induced by using the first h eigenactivities is no greater than ε_0 . We then call $h(\varepsilon_0)$ the *appropriate number of eigenactivities*.

Validity of Applying PCA in this Study

When PCA is used, the distribution of the original data is usually assumed to be multivariate Gaussian. The advantage of multivariate Gaussian assumption lies in that the principal components are not only uncorrelated but also mutually independent. When the principal components are independent of each other, it ensures that different components are measuring separate things, and the high dimensional distribution of the original data can be easily revealed by the distribution of each component, as the product measure can be easily constructed from the distribution measure of each component.

In this study, the original data is a Cartesian product of binary random variables, whose distribution is clearly non-Gaussian. However, as our purpose is not to run a regression or to reveal the high dimensional probability distribution of the original data using those principal components, the independence between

² In the generic case, \mathbf{u}_t has exactly one entry of value 1. When \mathbf{u}_t has more than one entries that are equal to 1, it must be the case that there are more than one $l \in \{1, \dots, 9\}$ such that $w_{t+288 \times (l-1)} = M_t$. In such a case, which is extremely rare or never happens, we keep the first entry 1 and change the others into 0.

1 components is not necessary.³ For this reason, PCA/eigen decomposition is widely
2 employed for dimension reduction in similar types of studies (Eagle and Pentland
3 2009; Turk and Pentland 1991; Calabrese et al. 2010).

4 The special binary property of the original data in this study strengthens
5 the power of eigen decomposition. Each entry A_{Dj} of the random vector \mathbf{A}_D only
6 takes values 0 and 1, and satisfies the compatibility condition mentioned
7 previously. The reconstruction algorithm introduced above takes full advantage of
8 it. In order for the reconstructed $\hat{\mathbf{a}}_i$ equal to the original observation $\mathbf{a}_i =$
9 $(a_1, \dots, a_m)'$, there is no need for \mathbf{w} to be very close to \mathbf{a}_i , which usually requires
10 a large number of eigenactivities to be employed in the reconstruction. Instead,
11 we only need that for any $t \in \{1, 2, \dots, 288\}$, $w_{t+288 \times (l-1)}$ is the largest in
12 $\{w_t, w_{t+288}, \dots, w_{t+288 \times 8}\}$, when $a_{t+288 \times (l-1)} = 1$. This property greatly lowers
13 the threshold for accurate reconstruction, which ensures low reconstruction errors
14 by using just a small number of eigenactivities.
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22 4.3 Daily Activity Clustering

23 To answer the second question raised in the beginning of Section 4, we propose to
24 use the K -means clustering algorithm, one of the most popular iterative clustering
25 methods, to partition individuals in the metropolitan area into clusters based on
26 their daily activity dissimilarity. In our study, although each of the observations
27 bears a “time stamp”, they are not repeated observations of the same phenomenon.
28 In other words, the data is not time series data intrinsically, and therefore we do
29 not employ time series clustering method here.⁴ However, time series clustering
30 method could be appropriate for other related research in clustering human
31 motions (Li and Prakash 2011).
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38 *K-Means Clustering and Categorical/Binary Data*

39 The K -means algorithm has been widely applied to partition datasets into a
40 number of clusters (Wu et al. 2008). It performs well for many problems,
41 particularly for numerical variables that are normal mixtures (Duda et al. 2001;
42 Bishop 2009). While its definition of “means” in some cases limits the K -means
43 application and leaves categorical variables not easy to treat (Xu and Wunsch
44 2009), a few studies have explored various ways to tackle this issue (Huang 1998;
45 Ordonez 2003; Gupta et al. 1999). Ralambondrainy (1995) proposes to convert
46 multiple categorical data into binary data (indicating if an observation is in the
47 specified category) and treat the binary attributes as numeric in the K -means
48 algorithm to cluster categorical data. Huang (1998) criticizes that the drawback of
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57 ³ In fact, Gaussian assumption is not necessary for PCA. Readers may refer to Jolliffe (2002) (page 396) for
58 discussion about Gaussian assumption and the relationship between PCA and *independent component*
59 *analysis* (ICA).

60 ⁴ For instance, the data about an individual’s activity in the time interval 6:55-7:00 a.m. and that in 7:00-7:05
61 a.m. can’t be viewed as two consecutive observations of one phenomenon. Instead, they should be viewed as
62 one observation of two phenomena that happen consecutively in time.
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1 Ralambondrainy's approach is the tremendous computational cost, since it needs
2 to handle a large number of binary attributes, especially when the number of
3 categories are large. Huang (1998) presents two variations of the K -means
4 algorithm (i.e., k -modes, and k -prototypes) for clustering categorical data. For
5 similar motivations, Ordonez (2003) presents three variations of the K -means.
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8 *K-Means Clustering via PCA*

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10 For our study, as discussed previously, we assume that within each of the 288
11 five-minute intervals of the entire day, an individual conducts one of the 9 types
12 of activities. We then convert the 288 entries of the categorical attributes of an
13 individual's daily activity into a 2592-dimensional binary vector. Our data
14 transformation process is similar to what Ralambondrainy (1995) proposes, which
15 allows us to apply the K -means clustering algorithm.
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18 When considering the options of dissimilarity measurements between
19 individuals' daily activity sequences, if following the most natural approach, one
20 could calculate the Euclidean distance $\|\mathbf{a}_i - \mathbf{a}_j\|$ between the two 2592-
21 dimensional vectors. However, as Huang (1998) points out, when the number of
22 binary attributes is large (in our case, 2592 dimensions), the computation cost is
23 very high. Alternatively, as PCA/eigen decomposition can reduce the dimension
24 of the problem significantly, a better approach is to measure the Euclidean
25 distance $\|\mathbf{y}_i - \mathbf{y}_j\|$ between the $h(\epsilon_0)$ -dimensional vectors \mathbf{y}_i and \mathbf{y}_j , where \mathbf{y}_i
26 and \mathbf{y}_j are the projection of \mathbf{d}_i and \mathbf{d}_j onto the first $h(\epsilon_0)$ eigenactivities. Since the
27 change of orthonormal bases does not affect the Euclidean distance no matter
28 whether the original or the new coordinates are used, the Euclidean distance
29 obtained from the coordinates of reduced dimension via PCA is very close to the
30 original one, and can be used as the dissimilarity measurement between
31 individuals' daily activity sequences.
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34 In the latter approach, the original 2592 dimensions will be reduced to a
35 much smaller dimension $h(\epsilon_0)$, and the computational cost is significantly lowered,
36 while the accuracy of clustering results is still maintained. Many studies have
37 demonstrated the successfulness of applying the K -means algorithm via PCA
38 (Ding and He 2004; Zha et al. 2001), and our study illustrates the effectiveness of
39 applying K -means via PCA when having categorical/binary data. The readers can
40 also see from later sections of the paper that our clustering results are very
41 significant and intuitively meaningful.
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44 *Cluster Validity*

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46 One problem that needs to be solved in the clustering process is to determine the
47 optimal number of clusters that best fits the inherent partition of the data set. In
48 other words, we need to evaluate the clustering results given different cluster
49 numbers, which is the main problem of cluster validity (Halkidi et al. 2001). There
50 are mainly three approaches to validate the clustering results, based on (1)
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external criteria, (2) internal criteria and (3) relative criteria, and various indices under each criteria (Brun et al. 2007). For our study, since we do not have pre-specified cluster structure, we use internal validation indices whose fundamental assumption is to search for clusters whose members are close to each other and far from members of other clusters. More specifically, we propose to use Dunn's index (Dunn 1973), and Silhouette index (Rousseeuw 1987) to help us select the optimal number of clusters.

5 Findings: Patterns of Human Daily Activity

In this section, we present our findings of the human activity patterns on an average weekday and weekend in the Chicago metropolitan area. (1) We compute the eigenactivities of all the sample individuals on an average weekday and weekend to identify the inherent daily activity structure of individuals in a metropolitan area. (2) By using the K -means clustering algorithm, we cluster the individual daily activities patterns for an average weekday and weekend, and their variation of daily activity types. We summarize the social demographic characteristics for each group of individuals, and find distinct patterns among the individuals within each group.

5.1 Eigenactivities

By employing the principal component analysis method discussed in the previous session, we derived the eigenactivities for an average weekday and weekend in the Chicago metropolitan area. Due to limited space, in this section we only display the first three eigenactivities for both the weekday and weekend cases.

Weekday

Figure 6 shows the first three eigenactivities of individuals in Chicago on an average weekday. We see that the first weekday eigenactivity (the 1st column of Figure 6) mainly describes the high probability of working (and low probability of staying at home) from 7:00 a.m. till 5:00 p.m. compared to the sample mean. The direction of the first eigenactivity on a weekday accounts for the largest variance of individuals' daily activities of the weekday data, which means that the major difference of individuals' daily activities on a weekday is if they are working or staying at home from 7:00 a.m. to 5:00 p.m. The second weekday eigenactivity (the 2nd column of Figure 6) reveals a high probability of schooling from 8:00 a.m. to 3:00 p.m. combined with a low probability of either staying at home during the same time period or working from 8:00 m to 5:00 p.m. (when compared to the sample mean in the data). The second eigenactivity direction accounts for the largest variance that is orthogonal to the first eigenactivity. The third weekday eigenactivity (the 3rd column of Figure 6) portrays a high probability of staying at home from 3:00 p.m. to 11:00 p.m., and a relatively high probability of working from 7:00 a.m. to 12:00 p.m., together with low probabilities of staying at home

from 7:00 a.m. to 11:00 am, working from 3:00 p.m. to 11:00 p.m., and recreation from 4:00 p.m. to 9:00 p.m. (all compared to the sample mean). The direction of the third eigenactivity accounts for the largest variance whose direction is orthogonal to the 1st and 2nd eigenactivities.

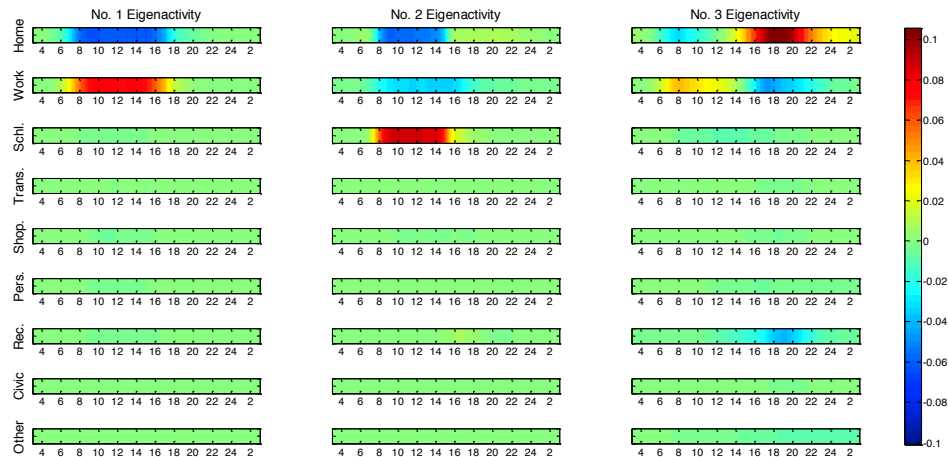


Figure 6 The first three eigenactivities of a weekday in Chicago

Weekend

Figure 7 illustrates the first three eigenactivities of individuals in Chicago on an average weekend. The first weekend eigenactivity (the 1st column of Figure 7) includes a high probability of recreating or visiting friends between 10:00 a.m. and 11:00 p.m., combined with a very low probability of staying at home from 8:00 a.m. to 9:00 p.m., and a somewhat high probability of working between 8:00 a.m. and 5:00 p.m., compared to the sample mean. The first eigenactivity of the weekend indicates that the largest discriminator of individuals' activities on a weekend is if they leave home from late morning to late evening, either for work or for recreational activities. The second weekend eigenactivity (the 2nd column of Figure 7) has a high probability of working from 7:00 a.m. to 4:00 p.m. and staying at home from 4:00 p.m. to the next early morning, combined with low probabilities of staying at home from 7:00 a.m. to 2:00 p.m. or recreating from 2:00 p.m. to 11:00 p.m. There is also some increased probability of engaging in civic or religious activities from 9:00 a.m. to 12:00 p.m. The second weekend eigenactivity (orthogonal to the first weekend eigenactivity), reveals that the 2nd largest clustering of individuals' activities during the weekend comes from either (a) working during the day time or conducting civic or religious activity in the morning, and then staying at home from late afternoon to the next early morning, or (b) staying at home during the morning and early afternoon and going out for recreation and entertainment in the early afternoon till late evening. The third weekend eigenactivity (the 3rd column of Figure 7) portrays high probability of staying at home from 3:00 p.m. to 11:00 p.m., and relatively high probability of working from 7:00 a.m. to 12:00 p.m.; combined with low probability of staying at home from 7:00 a.m. to 11:00 a.m., or working from 3:00 p.m. to 11:00 p.m., or

recreation from 4:00 p.m. to 9:00 p.m. (all compared to the sample mean). The direction of the third eigenactivity accounts for the largest variance whose direction is orthogonal to the 1st and 2nd eigenactivities.

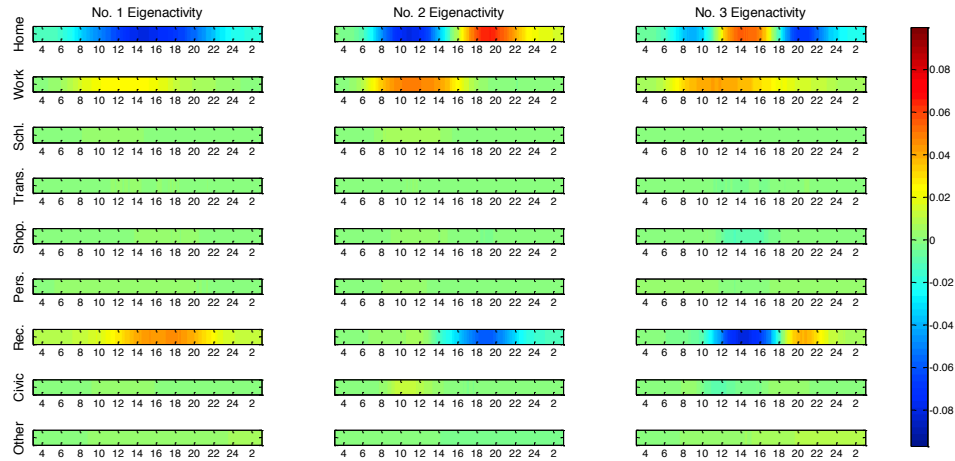


Figure 7 The first three eigenactivities of a weekend in Chicago

Selected Eigenactivities for Daily Activity Reconstruction

We employ the reconstruction error measure defined in Section 4.2 to select the appropriate number of eigenactivities that are good enough to represent accurately the elements in \mathcal{S} . In Figure 8 and Figure 9, the left panels show the relationship between eigenvalues and the rank of eigenactivities, and the right panels display the relationship between the reconstruction error and the number of eigenactivities used in the activity reconstruction. We can see that the eigenvalues decrease very fast with the ascending rank of eigenactivities. We find that 21 eigenactivities for an average weekday, and 18 eigenactivities for an average weekend, will allow us to reconstruct a weekday and weekend daily activity sequence for individuals in the metropolitan area with an average 1% error, which means that for an average sample there are about 26 ($\approx 2592 \times 1\%$) entries (or 13 of the five-minute intervals) of our reconstructed daily activity sequence that are different from the original observed data. It is equivalent to say that we have around one-hour estimation error in recovering an individual's daily activity sequence when using 21 eigenactivities for a weekday, or 18 eigenactivities for a weekend. Considering that a whole day is divided into 288 five-minute intervals and we have 9 activities in total, this reconstruction precision is very satisfactory.

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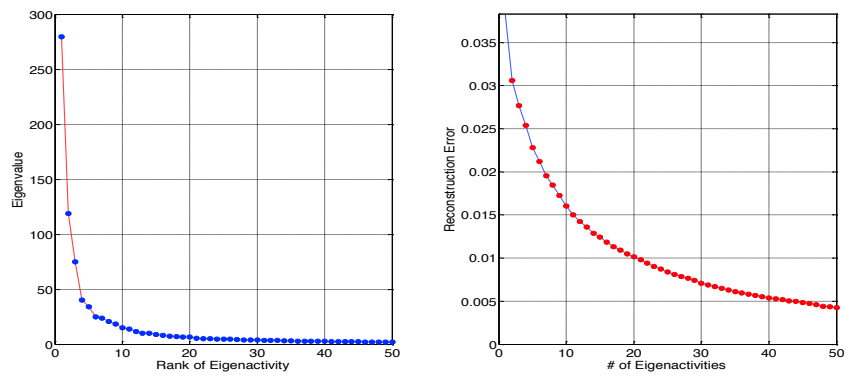


Figure 8 The eigenvalue and the reconstruction error w.r.t. the rank of eigenactivity of a weekday

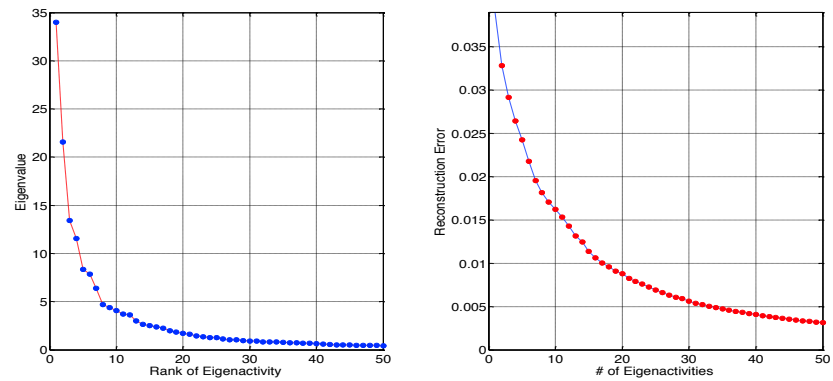


Figure 9 The eigenvalue and the reconstruction error w.r.t. the rank of eigenactivity of a weekend

Figure 10 exhibits our reconstructed individuals' daily activity sequence during the weekday and weekend, using the 21 eigenactivities for the weekday, and the 18 eigenactivities for the weekend, respectively. Comparing this figure with Figure 5 we can see that, in general, our reconstructed daily activities match the original sample data very well, except that at the 1% error level it does not allow us to reconstruct the activities in the "Transportation Transitions" category very accurately. Recall that this category involves not very common activities such as, "changing type of transportation/transfer; dropping off passenger from car; picking up passenger; service private vehicle; and loop trips" as described in Table 1.

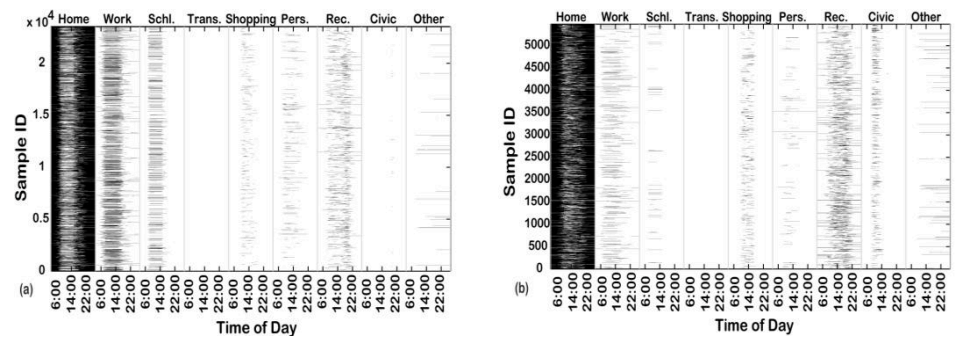


Figure 10 Reconstructed individual activities for samples on a (a) weekday and (b) weekend in Chicago

5.2 Clustering Individuals' Daily Activities and Social Demographics

In this section, we employ the K -means clustering via PCA method discussed in Section 4.3 to identify groups of individuals in the metropolitan area based on their daily activity sequences during the weekday and the weekend. We use two major cluster validity indices to determine the optimal number of clusters for the weekday and weekend case. After clustering individuals in the Chicago metropolitan area based on their daily activity sequence, we also summarize the social demographic statistics of the different groups, and find interesting and suggestive signatures among clusters.

The Average Weekday

We use the Dunn's index (Dunn 1973) and the average Silhouette index (Rousseeuw 1987)—for both of which the higher the value the better the clustering—to identify the appropriate number of clusters for the K -means clustering (Brun et al. 2007). Figure 11 shows the value of the indices with respect to the number of clusters.

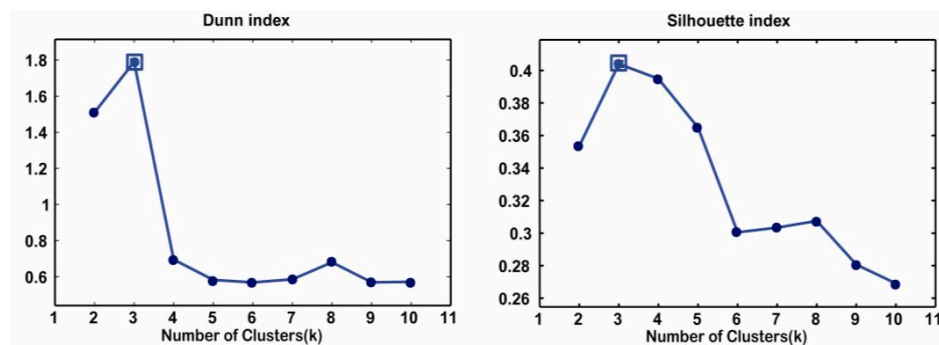


Figure 11 Cluster validity indices for the weekday case

Both the Dunn's index and the Silhouette index suggest that when the cluster number is 3, it gives the best clustering results for the average weekday case. This corresponds to three commonly identified groups of the population: (I) students (13%), (II) workers (33%), and (III) people who spend most of their time at home (54%). We then use our method to future explore the diversity within the population. From the Dunn's index and the Silhouette index (in Figure 11) we can see that the cluster number of eight is relatively good.

Figure 12 exhibits the K -means clustering via PCA results (with cluster number=8), revealing individuals' activity patterns on an average weekday and their social demographic characteristics. Each row of the figure describes different information for the same cluster, while each column portrays temporal effects in different ways. The order of the clusters (in the row) is organized by the dendrogram of the hierarchical structure of the clusters, presented in the last column. The horizontal length of the hierarchical dendrogram measures the average distance between the two clusters being connected (Duda et al. 2001).

The first column of Figure 12 displays individuals' daily activity

1 sequences for each cluster. The second column shows the aggregated volume of
 2 different types of activities in the metropolitan area during a specific time interval
 3 over 24 hours, and the third column is a zoomed-in view of the previous column.
 4 The fourth column presents the social demographic statistics of the cluster in that
 5 row. We use a Star Diagram (Figure 13) to represent the average social
 6 demographic characteristics of each cluster summarized in Table 2. By mapping
 7 the relationship between the two clustering alternatives, we are able to explore in
 8 detail the subdivisions within the previously identified three clusters (see Table 3).

13 Table 2 Statistics on social demographics of the total sample and each cluster on a weekday

| | Social Demographic Variables | Sample Mean | Mean of Cluster | | | | | | | |
|----|------------------------------|-------------|-----------------|-------|-------|-------|-------|-------|-------|-------|
| | | | #2 | #8 | #7 | #4 | #6 | #3 | #5 | #1 |
| 17 | 1 Female | 53.3% | 55.0% | 49.0% | 46.7% | 57.3% | 57.7% | 58.9% | 50.1% | 44.9% |
| 18 | 2 Student | 22.1% | 16.4% | 91.1% | 13.2% | 22.5% | 13.2% | 15.7% | 8.3% | 7.2% |
| 19 | 3 Homemaker | 13.4% | 12.9% | 3.5% | 11.1% | 12.8% | 15.1% | 12.0% | 13.4% | 21.3% |
| 20 | 4 Retired | 59.7% | 66.3% | 8.9% | 61.1% | 58.3% | 62.5% | 70.7% | 54.9% | 53.2% |
| 21 | 5 Work | 53.4% | 51.1% | 12.1% | 95.4% | 42.8% | 33.7% | 38.4% | 94.1% | 95.0% |
| 22 | 6 Part Time | 20.4% | 15.9% | 52.3% | 28.6% | 36.2% | 29.7% | 39.5% | 10.9% | 12.7% |
| 23 | 7 No Flexibility | 34.4% | 24.2% | 36.4% | 43.0% | 26.2% | 27.8% | 22.8% | 32.8% | 46.8% |
| 24 | 8 Some Flexibility | 42.3% | 47.1% | 44.4% | 39.9% | 36.0% | 35.8% | 37.2% | 50.3% | 40.8% |
| 25 | 9 Much Flexibility | 23.2% | 28.7% | 19.2% | 17.1% | 37.8% | 36.4% | 40.0% | 17.0% | 12.4% |
| 26 | 10 Work at Home | 8.1% | 11.3% | 5.9% | 3.1% | 17.5% | 19.8% | 15.4% | 2.5% | 1.8% |
| 27 | 11 Edu.>Tech School | 45.9% | 55.3% | 6.5% | 48.3% | 45.8% | 40.3% | 46.5% | 72.5% | 58.9% |
| 28 | 12 Low HH Income | 16.9% | 19.6% | 14.4% | 19.4% | 17.1% | 24.3% | 19.3% | 7.8% | 10.0% |
| 29 | 13 Middle HH Income | 32.5% | 28.0% | 28.1% | 34.4% | 35.1% | 33.4% | 35.6% | 28.8% | 35.0% |
| 30 | 14 High HH Income | 50.7% | 52.4% | 57.4% | 46.2% | 47.8% | 42.3% | 45.1% | 63.4% | 55.0% |
| 31 | 15 The Young (age<35) | 34.6% | 30.4% | 92.4% | 30.8% | 32.5% | 27.8% | 26.1% | 24.9% | 20.3% |
| 32 | 16 The Middle-aged | 39.7% | 38.0% | 5.0% | 55.7% | 32.5% | 32.7% | 31.4% | 62.3% | 66.4% |
| 33 | 17 The Older (age>60) | 25.8% | 31.7% | 2.5% | 13.5% | 34.9% | 39.6% | 42.4% | 12.8% | 13.3% |

39 Table 3 Cluster Mapping: Clusters of individuals based on their weekday activities

| Clusters of Eight | | % in Total | Share in Cluster | | | Clusters of Three | |
|-------------------|--------------------------|------------|------------------|--------|---------|------------------------|------------|
| Clusters | | | I | II | III | Clusters | % in Total |
| 43 | #8 Students | 12.50% | 99.80% | 0.00% | 0.20% | I Students | 12.90% |
| 44 | #5 Regular workers | 17.90% | 0.00% | 99.90% | 0.10% | II Traditional Workers | 33.20% |
| 45 | #1 Early-bird workers | 13.50% | 0.00% | 99.20% | 0.80% | | |
| 46 | #7 Afternoon workers | 3.10% | 2.70% | 32.40% | 64.90% | | |
| 47 | #2 Overnight adventurers | 1.30% | 4.80% | 26.40% | 68.80% | | |
| 48 | #4 Afternoon adventurers | 5.50% | 1.90% | 3.20% | 94.90% | III + Stay-at-home | 53.90% |
| 49 | #6 Stay-at-home | 33.20% | 0.00% | 0.00% | 100.00% | | |
| 50 | #3 Morning adventurers | 13.00% | 1.30% | 2.90% | 95.80% | | |

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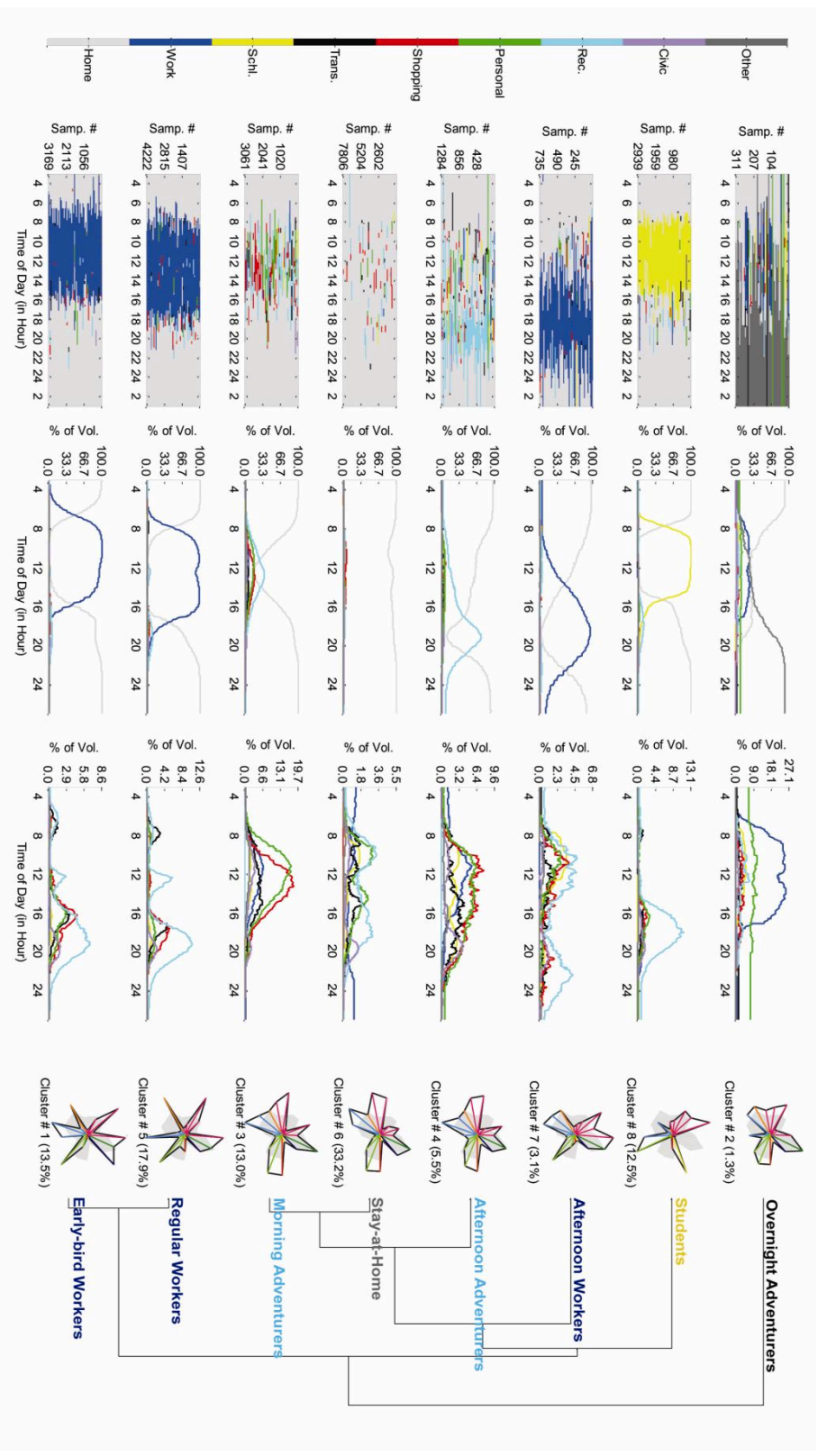


Figure 12 Clustering of individuals' weekday activity patterns and their social demographic characteristics in Chicago (cluster number=8).

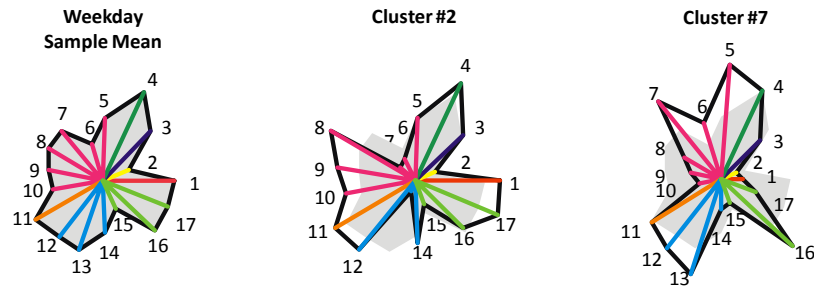


Figure 13 A Demonstration of the Star Diagram of the cluster's social demographics on a weekday
 Note: In this Star Diagram, we use different colors to represent different vectors of each cluster (corresponding to the numbered social demographic variables in Table 2), and also set the sample mean as the gray background for each cluster for comparison convenience.

In the following paragraphs, we discuss specifically the clustered individual activity patterns of a weekday in each of the eight clusters and their social demographic characteristics (shown in Figure 12).

Students: Cluster #8 consists of students who go to school during the day time, and go out for meal, recreation or entertainment starting from 3:00 p.m. to around 10:00 p.m. This group shares 12.5% of the total sample. The average annual household income for the cluster members is higher than the average weekday sample mean, and over 92% of cluster members are under 35 years old.

Regular Workers Cluster #5 is the group of workers who have a relatively regular schedule. They leave home for work at around seven to eight in the morning, and finish work at around five to six in the late afternoon. Some of them go out for meal or recreation at lunch break time. Some do similar activities in the late afternoon, with a peak of 5% them doing shopping at 6:00 p.m., and another peak of 12% dining, recreating or entertaining at around 7:00 p.m. There is also a small proportion of the group members engaged in “*transportation transition*” activities in the early morning and late afternoon.

Early-Bird Workers Individuals in Cluster #1 have similar daily activity pattern to those in Cluster #5, except for the overall time shift—members in Cluster #1 start their day about one hour earlier than folks in Cluster #5 in general. While the rhythms of other activities of the two clusters are similar, Cluster #1 seems to have a lower share of peak volume in other activities compared to those of Cluster #5. When we compare the social demographic characteristics of the two clusters, the early-birds workers in Cluster #1 live generally less flexible lives and tend to have a lower educational level and household income level, and there are a greater proportion of them in the middle-aged group (between the age of 35 to 60), compared to their counterparts of the regular workers in Cluster #5.

Afternoon Workers For members in Cluster #7, a large proportion of them work but their daily activity rhythm are quite different from those in Clusters #1 and #5. The majority of them (64.6%) spend their morning at home, and for a small proportion, they go shopping (with a 3% peak at 11 a.m.) or do personal business (with a 2% peak at 10 a.m.) or recreation (with 4.5% peak around noon time). Most of them start work around noon to early afternoon (from 12:00 p.m. to

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1:00 p.m.) and finish work very late (from 10:00 p.m. in the evening till midnight or early the next morning). Some of them also do recreational activities after work in the evening (with a 4.5% peak at around 11:00 p.m.). Only 3.1% of the total weekday samples belong to this cluster. The social demographic characteristics of this group are somewhat similar to those of members in Cluster #1 (the early-bird workers), except that Cluster #7 members have lower average educational level and lower household income. The middle-aged population share of this cluster is higher than the weekday sample mean.

Stay-at-home We call Cluster #6 members "stay-at-home" because they spend most of their time at home with only a few of them (3%) conducting personal business or recreational activities over the day. This cluster is large in size and constitutes 33.2% of the total weekday sample, and has a higher share of females, a higher share of older population, a lower average educational level, and a lower household income level, compared to the weekday sample mean. It also has the greatest share of members who work at home (19.8%) compared to the other clusters. Members in this cluster also claim to have very flexible schedules.

Morning & Afternoon Adventurers Members in Clusters #3 and #4 are similar to "stay-at-home" persons in Cluster #6 except that a greater share of them go out for shopping, recreation and personal business either in the morning (the "morning adventurers ") or in the afternoon (the "afternoon adventurers "). The majority of the Cluster #3 members stay at home most of the time, and only some of them go out in the morning for recreation/entertainment, social activities (with a peak around 30% of them at noon), for shopping and personal business (with a peak around 13% around noon). 6.6% of them do some work in the morning too. While most members of Cluster #4 stay at home during the day time, they start their recreational/ entertainment/ social activities in the late afternoon, with a peak of 66% of them at around 7:00 p.m. in the evening. A smaller proportion of Cluster #4 members do shopping or personal business during the day time (around 6% of peak volume). Cluster #3 and #4 members share similar social demographic characteristics. Compared to the total weekday sample mean, these two clusters have greater shares of females and older population, higher shares of people who work at home or whose schedule is flexible, lower share of workers and lower household income level. In total, there are 13% of total weekday samples in Cluster #3, the "morning adventurers ", and 5.5% in Cluster #4, the "afternoon adventurers".

Overnight Adventurers We call Cluster #2 members "overnight adventurers" because only a quarter of them work during the day and the majority of members in this group do "other" activities (that are not specified in their survey report) from early afternoon till midnight. There are only 1.3% of the total weekday sample in this cluster, among which three quarters claim to have some or great schedule flexibility, and 11.3% work at home. Their educational level is higher than the population mean, yet lower than the regular workers and the early-

bird workers. The share of the older population in this group is unexpectedly higher than the weekday sample mean.

The Average Weekend

We conduct similar analysis on the average weekend samples, and discuss the findings in this section. Based on the Dunn's Index and the average Silhouette Index (see [Figure 14](#)), we find that the optimal number of cluster size is three, which divides the total weekend samples into groups of (I) "adventurers" (26.3%), (II) "weekend workers" (7.7%), and (III) the "stay-at-home" (66.0%).

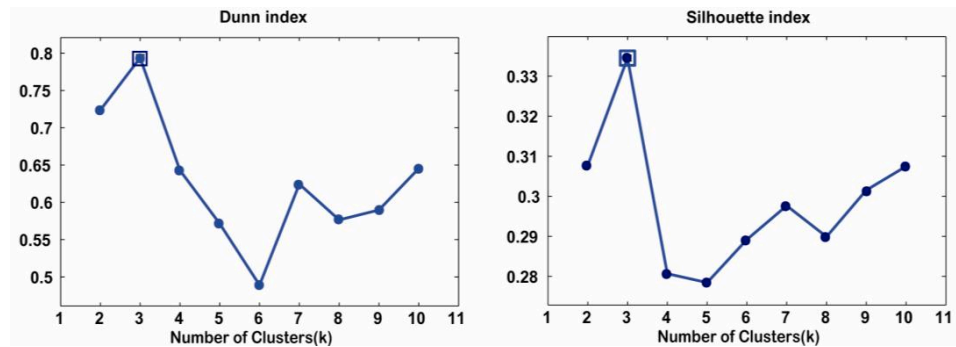


Figure 14 Cluster validity indices for the weekend case

In order to further explore detailed submarkets of the individuals' weekend activity patterns, we choose the cluster number (=7) that gives the second best clustering results. The seven clusters are described in [Table 4](#) and associated with the broader categories from the earlier three-clusters. We can see that there are four submarkets of the "adventurers" group (including overnight adventurers with known and unknown activities, afternoon adventurers, and evening adventurers), two submarkets for the "stay-at-home" group (including afternoon stay-at-home, and all-day stay-at-home) and one single market for the "weekend workers".

Table 4 Clusters Mapping: Clusters of individuals based on their weekend activities

| Clusters of Seven | | % in Total | Share in Cluster (size=three) | | | Clusters of Three | | |
|-------------------|-------------------------------------|------------|-------------------------------|--------|-------|-------------------|-----------------|-------|
| Clusters | | | I | II | III | Clusters | % in Total | |
| #1 | Overnight adventurers (unspecified) | 1.6% | 91.0% | 0.0% | 9.0% | I | Adventurers | 26.3% |
| #3 | Overnight adventurers | 2.5% | 98.6% | 1.4% | 0.0% | | | |
| #7 | Afternoon adventurers | 12.4% | 87.9% | 0.7% | 11.4% | | | |
| #5 | Evening adventurers | 11.7% | 81.9% | 0.2% | 17.9% | | | |
| #2 | Workers | 7.4% | 0.0% | 100.0% | 0.0% | II | Weekend workers | 7.7% |
| #4 | Afternoon stay-at-home | 44.1% | 0.1% | 0.0% | 99.9% | III | Stay-at-home | 66.0% |
| #6 | All day stay-at-home | 20.3% | 9.1% | 1.2% | 89.8% | | | |

Similar to our handling of the weekday case, we use the "star diagram" to describe the group profiles and summarize their social demographic characteristics in [Figure 15](#). In order to differentiate the activities on different days

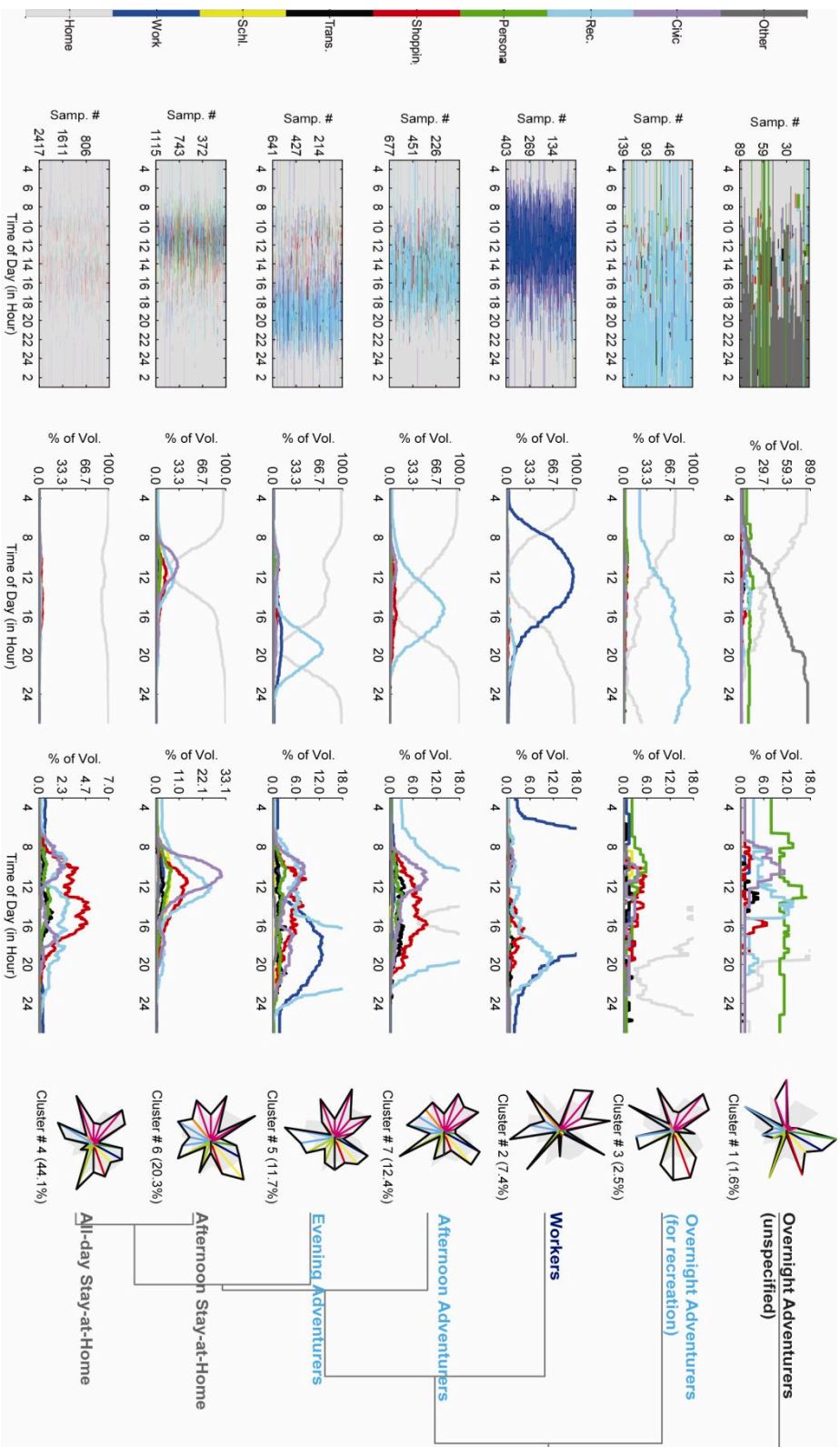
(Saturday or Sunday) we add a new variable (the share of Saturday samples) as the first vector, and retain the other factors described in the weekday star diagram. Since we have a slightly large number of samples on Saturday than on Sunday, the total weekend population mean has a higher share of Saturday activities. We summarize the signature profiles of the social demographic characteristics of all seven clusters in [Table 5](#)

Even though the majority of people are either stay-at-home (66%) or enjoying their social life (26.3%), there are still a group of them working during the weekend, consisting of 7.4% of the total weekend sample. These people have a schedule that is similar to the regular workers on the weekdays—they leave home for work around seven to eight in the morning, and finish work around five to six in the afternoon. A few of them go out for recreation/entertainment after work in the early evening, with a peak around 12% at 8:00 p.m. There is a greater share of people working on Saturday than on Sunday, and there are more males than females who work during the weekends, compared to the weekend sample mean.

Table 5 Social Demographic Characteristics of the Weekend Activity Clusters

| Clusters | % in Total | Social Demographic Characteristics, Compared to Weekend Total Sample Mean |
|--|------------|--|
| #1 Overnight adventurers (unspecified) | 1.6% | More on Sunday; Greater share of female; Higher share with much flexibility; Higher share of low household income; Lower average education level; Grater than average elderly people. |
| #3 Overnight adventurers | 2.5% | More on Saturday, Greater share of female; Greater share of students; Greater share with not flexible work schedule; Lower average educational level; Higher share of either low or high household Income; Higher share of young population. |
| #7 Afternoon adventurers | 12.4% | Mix of Sunday and Saturday; Mix of female and male; Higher share of students; Mix in work flexibility; Relatively high education level; Mixed income level; High share of young population. |
| #5 Evening adventurers | 11.7% | More on Saturday; High share with some work flexibility; Higher share with high income households; Fewer elderly population. |
| #2 Workers | 7.4% | A bit more on Saturday; Lower share of female; Lower share of students; Higher share of people who work; Higher share with no work flexibility; Relatively high education level; High share of middle and high household income; Higher share of middle-aged population. |
| #6 Afternoon stay-at-home | 44.1% | Much more on Sunday; Higher share of female; Higher share of students; Higher share with some or much work flexibility; Higher share of people who work at home; Higher than average educational level; Higher share of low or high income household income; Higher share of young population. |
| #4 All-day stay-at-home | 20.3% | More on Saturday; Higher share of female; Lower share of students, Lower share of people who work; Higher share with no work flexibility; Lower than average educational level; Higher share of low household income; More elderly population. |

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6 Conclusions and Discussion

In this section, we summarize our methods and major findings and discuss potential implications of this study and future work.

6.1 Summary

In this paper, we analyze the activity patterns for 23,527 individuals on an average weekday and 5,481 individuals on an average weekend in the Chicago Metropolitan Area, by dividing the entire day into 288 five-minute intervals. We define the eigenvectors of the covariance matrix of the activity data as Eigenactivities, which are a set of vectors that span an ‘activity space’ and characterize the differences between individuals’ daily activities in the metropolitan area. A linear combination of the metropolitan area’s eigenactivities can accurately reconstruct the activity pattern of each individual. Based on a small activity reconstruction error (1%), we select 21 and 18 primary eigenactivities for the weekday and weekend case respectively to represent individuals’ daily activities in the metropolitan area. We perform a K -means clustering algorithm on the obtained eigen decomposition projections to partition the samples into k clusters. By reducing the dimension of the problem with a small number of eigenactivities, we lower the computational cost of the method.

We successfully cluster individuals in the metropolitan area into groups within which they have relatively homogeneous daily activity patterns, and across which they have heterogeneous diversity. We cluster all the weekday samples into eight detailed categories including students (12.50%), regular workers (17.90%), early-bird workers (13.50%), afternoon workers (3.10%), the stay-at-home (33.20%), the morning adventurers (13.00%), the afternoon adventurers (5.50%) and the overnight adventurers (1.30%). For the weekend case, we cluster people into seven categories including the weekend workers (7.4%), the afternoon stay-at-home (44.1%), the all-day stay-at-home (20.3%), the afternoon adventurers (12.4%), the evening adventurers (11.7%), the overnight adventurers (for recreation—2.5%, and with unspecified activities—1.6%).

We identify the signatures of the social demographic profile of each cluster. In general, we find that, for the weekday case, when compared with the sample mean (1) the weekday workers have a lower share of females; but higher share of the middle-aged population, people who have no flexibility in work schedule and who have higher education, and/or higher household income level. (2) The weekday “adventurers” have a higher share of female, older population, people who work at home, and/or whose schedule is more flexible; and a lower share of students, working people, and people who have lower educational level, and/or lower household income level. For the weekend case, we find that (1) the profile of the weekend workers is very similar to those of the weekday workers, and (2) while comparing the “stay-at-home” with the “adventurers”, the former

1 have a higher share of female, older population, low income households and
2 people who work at home; and lower share of students and people who work.

3 4 6.2 Research Implications for Future Work

5
6 By applying a public available travel survey data, and employing the *K*-means
7 clustering via PCA methods, this study reveals the regular patterns of human daily
8 activities which reinforce previous findings on high predictability of human
9 mobility using large-scale data sets (Song et al. 2010; Wang et al. 2011a;
10 Gonzalez et al. 2008). The activity groups found here constitute a basic piece of
11 information on urban activities that can be used to enrich models extracted from
12 other sources of large-scale urban sensing data, i.e., mobile phones or Wi-Fi
13 access points. To these means, sensing data must be combined with spatially
14 detailed GIS data (such as land use data and points-of-interests data). The
15 framework of our study also allows us to link the temporal dimension with the
16 spatial dimension, as we not only transform the traditional travel and activity
17 survey into individuals' activity types at each time interval but also could impute
18 their location information. This information combined with data mining and
19 statistical learning methods could represent advances in urban transportation
20 questions, which are essential but lacked enough information in the past.

21
22 Taken together, the significance of clustering people based on their daily
23 activity patterns sheds lights on potential future applications in urban and
24 transportation planning, emergency response and spreading dynamics. For
25 example without heavy-burdened computational costs, urban and transportation
26 researchers may understand activity-based signature of daily travel patterns for
27 different types of individuals, and/or construct individuals' mobility networks.
28 Knowing more about the links between land use and activity patterns could
29 facilitate congestion management, and improve models that try to predict human
30 mobility, estimate origin-destination (OD) matrices, and/or simulate travel
31 patterns under different circumstances. As demonstrated by Wang et al. (2009),
32 Balcan et al. (2009), and Wang et al. (2011b), improvement in human mobility
33 prediction models also has important implications in modeling and estimating the
34 spreading of mobile phone viruses, infectious diseases, and information
35 dissemination.

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