An Analysis of the Day-to-day Variability in the Individual's Action Space: An Exploration of the Six-Week *Mobidrive* Travel Diary Data

by

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Abstract

Using six-week travel diary data from Karlsruhe and Halle, Germany, this paper examines the characteristics of individuals' action space. The extension of action space is represented by the second moment of the activity locations it contains. Day-to-day variations in the second moment are examined while taking unobserved heterogeneity across individuals into account. The results show that activity orientation (e.g., obligatory activities on weekdays and discretionary activities on weekend days) influences the extension of action space. The extension of action space is also associated with the individual's residence location and socio-economic attributes. The inner-city residents tend to have large variations in the second moment, and workers have larger moments than do non-workers and students. The statistical analyses of the variance of the second moment of activity locations have revealed that, on weekdays, the spread of activity locations and the distance from home to the centroid of activity locations are relatively stable from day to day. On weekend days, within-person variations in the second moment are larger, while unobserved heterogeneity across individuals accounts for a smaller portion of the total random variations.

INTRODUCTION

Individuals' daily lives consist of activities in space and time, and the activities that structure them, such as personal care, family interaction, work, shopping, recreation and socializing, occur at a relatively few geographic locations and for limited durations. In order to take part in activities, individuals often have to travel between different places. Their ability to travel in space and time depends in part on the resources available to them, e.g. time, money, and the automobile. Individuals' daily travel patterns and activity locations evolve under the constraints of these resources. Also influential are institutional, social, environmental and transportation network conditions. These factors affect the set of places where an individual visits to carry out activities. This set shall be called *action space*.

It is important to examine the characteristics of the action space of urban residents because such an examination will aid in evaluating their ability and flexibility in pursuing daily activities under the various constraints. Of course care must be exercised in such an evaluation because high mobility has dual implications—that one is capable of pursuing activities at various locations, and that one must travel to various locations in order to satisfy his needs. From the former perspective, high mobility is desirable, while from the latter viewpoint travel is a necessity to be minimized. From this latter viewpoint high mobility simply implies the presence of some deficiencies in urban activity-transportation system. In any event, an individual's ability in engaging in activities is linked to the level of welfare. In this sense the examination of action space is one of the primary concerns of transportation planning.

Action space has often been examined, most typically using cross-sectional data, and also with panel data in a few recent studies. The day is used to define the action space of an individual in many of these studies simply because the data used were daily data (e.g., Djist, 1999; Timmermans et al., 2003). One-day data, however, reveal only limited aspects of travel behavior as researchers have well articulated (e.g., Hanson and Huff, 1982; Pas, 1988). Reflecting on our own daily travel patterns would make it obvious that people do not repeat the same travel pattern everyday. The question that then arises is how to define an individual's action space when it varies from day to day. The notion of "typical" daily patterns (Hanson and Huff, 1988) has emerged as one of the key concepts in addressing the variability in daily travel patterns. Yet, a typical pattern reveals little about the variability in travel patterns and action space.

Even when data are available for multiple days, how the day-to-day variations in action space can be best captured is not obvious. The main reason for this is presumably the fact that travel patterns are multi-faceted; there are a number of ways in which a travel pattern can be characterized. For example, a very simple scheme has been adopted to characterize daily travel patterns by whether a trip for a particular purpose is included in them or not (Kitamura, 1988). One may focus on simple indices such as the number of trips or trip chains to represent travel patterns. More elaborate multi-variate analytic procedures are adopted to develop classification schemes by which any travel pattern is identified as one of a manageable number of travel pattern classes (e.g., Kansky, 1967; Oppenheim, 1975; Pass, 1988; Joh et al., 2001). This issue of representation also arises when one wishes to examine the variability in action space, whether across individuals or from day to day for a given individual.

One cannot fully characterize an individual's action space without knowing how it varies from day to day. Yet, variability in action space has rarely been explored before. The only study that authors were able to find which addresses the temporal variability of the individual's action space, is by Srivastava and Schönfelder (2003). With the *Mobidrive* travel diary data (see below) and Upssala survey data (Hanson and Huff, 1988), they compared the area of an individual's potential action space across two-week periods. In this study, the variability among individuals and day-to-day variability within each individual are not analyzed.

This study is an attempt to explore the day-to-day variability in the action space of urban residents. The analysis focuses on the association between the extension and variability of an individual's action space, and his attributes and also unobserved heterogeneity across individuals. The analysis of this paper is based on the representation of the extension of action space in terms of the second moment of the activity locations it contains with respect to their centroid, and the second moment of the centroid with respect to the home location. The analysis uses the *Mobidrive* data set, which was obtained from a six-week travel diary survey conducted in Karlsruhe and Halle, Germany, in 1999, and represents a total of 317 individuals over 6 years of age from 139 households (Axhausen et al., 2002).

Examining the day-to-day variability in the individual's action space is anticipated to enhance our understanding of travel behavior as it will provide opportunities to probe into the relation between potential and actual action spaces, spatial and temporal fixities of activities, their regularity, variability and diversification, or the binding effects of mandatory routine activities such as work. There are several hypotheses that guide this study, including:

- As workers tend to have more rigid activity schedules than non-workers and student, they will have less variable action spaces and more stable moment values than the others.
- Regardless of employment status, individuals tend to have routine activities at fixed locations or/and times on weekdays, and therefore an individual's weekday action spaces will exhibit less within-person variation.
- On weekend days, when individuals tend to pursue more discretionary activities, their action spaces will be more variable across weekend days.
- Since engagements in discretionary activities reflect individuals' tastes and preferences, action spaces on weekend days are more variable across individuals than those on weekdays.

The previous studies, especially those on the concept of spatial movement and action space, are discussed in the next section. In the following sections, the concept of second moments of activity locations and the *Mobidrive* data set used in this study are described. Results of descriptive analyses of second moments and those of model estimation are then presented. The paper is concluded with a section that offers a summary of results.

THE CONCEPT OF SPATIAL MOVEMENT AND ACTION SPACE

The term, action space, has been used to refer to different concepts. In particular, it has been applied to refer to a set of potential activity locations, and the set of locations where activities are actually pursued. Lenntorp (1976) notes that the individual's possibilities of engaging in events and processes are constrained and depend on a set of circumstances linked to the individual as well as to his environment. Consequently, the individual's reach ability is limited. The volume in space and time in which the individual's physical presence is possible is called *prism*. Hägerstrand (1970) notes that a prism is in part defined by constraints, including *capability constraints, coupling constraints*, and *authority constraints*. For descriptions of these concepts and their applications to travel behavior analysis, see Burns, (1979), Kitamura et al. (1981), Jones et al., (1983), Damm (1983), Jones et al, (1990), Axhausen and Gärling (1992), and Ettema and Timmermans (1997).

Governed by these constraints, and also conditioned by the urban environment and transportation networks, the individual’s daily travel and activity engagement evolves in space and time. This generates a distribution of locations where activities are pursued. *Action space*, or *activity space*, is defined as “the set of places where the individual frequents for a particular period of time to carry out particular activities” (Dangschat et al., 1982, p. 1155). An individual’s action space depends strongly on the locations of those activities to which the individual is committed, and if the locations are fixed in both space and time, they tend to act as “pegs” around which other activities are arranged (Pred, 1977). Golledge and Stimpson (1997, p. 279) point out:

> “The activity space for a typical individual will be dominated by three things: (1) movement within and near the **home**; (2) movement to and from **regular activity locations**, such as journeys to work, to shop, to socialize, and so on; and (3) movement in and **around the locations where those activities occur**” (emphasis in original).

In addition, the action space of an individual also depends on temporal constraints associated with activity locations.

As the discussions so far indicate, action space may be interpreted as a set of potential opportunities where activities can possibly be pursued given a set of governing constraints. This may be called *potential action space*. Djist (1999) notes that “Theoretically, the actual action space is situated within the potential action space.” In addition, there is a set of opportunities that the individual perceives as potential activity locations. Dijst (1999) calls this *perceptual action space*, which “covers the *actual action space*. The potential action space can be covered entirely by the perceptual action space. As a consequence of imperfect knowledge by people, in practice a large part of the potential action space will be situated outside this subjective action space.” Operationalizing these concepts, however, involves many measurement issues, including most obviously that perceptual action space is difficult to observe.

Several approaches have been adopted in the analysis of an individual’s action space. The simplest is just to show on a map the geographical distribution of the locations where a particular set of individuals engaged in activities. Markov chains are adopted by Horton and Wagner (1969) on a simple zone system to measure the extent of individuals’ action spaces. Beckmann et al. (1983) describe the action space of an individual in an abstract city as the volume of reachable opportunities. Note that both spatial accessibility of an opportunity and the amount of time that can be spent there are taken into account in this measure. This is an extension of the work by Burns (1979) in which one-dimensional representation of urban space is adopted. Lenntorp (1976) has developed a prototype simulation program to analyze an individual’s potential choices of time and location for food purchase while incorporating various alternatives for activity engagement and travel. Following these efforts, there are on-going efforts that attempt to develop rigorous methodologies for time geographic and activity analysis with GIS software (Miller, 2004) or using micro-simulation model systems (Arentze et al., 2001).

Schönfelder and Axhausen (2003), with the *Mobidrive* six-week travel diary data, deploy the confidential ellipse, kernel densities, and minimum spanning tress (network) methods to describe the individual's actual action space. The association between the individual's socioeconomic attributes and the characteristics of the calculated action space is analyzed by generalized linear models. The analyses show that contributing factors are not stable between two cities (Karlsruhe and Halle) and between representation methods (minimum spanning network and kernel densities).

Further, using the *Mobidrive* data and Uppsala survey results, Srivastava and Schönfelder (2003) compare the areas of individuals' action spaces across days of the week (workdays, Saturday and Sunday). Action space is evaluated based on locations visited over two-week periods. The results indicate that two-week action spaces tend to repeat themselves over the six-week study period.

Using activity and travel diary data for three consecutive days (Thursday through Saturday) obtained from two-worker families in two adjacent Dutch municipalities of Utrecht and Houten, Dijst (1999) represents an individual's action space as an ellipse, circle and line. A *reachable distance* is defined by deploying the notion of travel time ratio, i.e., the ratio between the travel time and the sum of the travel time and the activity time at the destination, developed in Dijst and Vidakovic (2000). Cluster and discriminant analyses are applied to group action spaces of different characteristics and to predict the type of actual action space and potential action space for each individual, given his socioeconomic attributes and time allocation.

As this brief review may indicate, knowledge is yet to be accumulated on the day-to-day variability in daily action space, i.e., a set of locations visited during the day. Likewise little is known about the association between the characteristics of action space and the individual's attributes, transportation networks, or urban structure. In fact some speculate such an association is weak, if not nonexistent. For example, Timmermans et al. (2003, p. 45) note: "As far as the relationships between spatial context, transportation system and space-time consumption patterns is concerned, we found little evidence of such a relationship, at least at the chosen level of (spatial) aggregation, after accounting for the differences between cities and regions. … There is some evidence that people in suburban locations, and people in urban locations with poor transport tend to chain more destinations in a single trip, but this relationship is weak and not significant." Timmermans et al. continue to conclude: "Within a particular society, psychological principles seem more important in shaping activities than the specific characteristics of the urban structure and the transportation system …"

In this context, it is noteworthy that the roles of unobserved heterogeneity across individuals in the evolution of an individual's action space have not been explored at all so far. An axiom in behavioral research is that an individual's behavior is dependent on his perception of the environment rather than on the actual construction of the environment itself. Horton and Reynolds (1971) and Dangschat et al. (1982) have noted that even when a group of individuals had perfect information concerning opportunities and their locations, their mental maps and the perceptions of urban space would differ across individuals.

The purpose of the study is to examine the individual's action space, as represented by the second moment of the activities locations contained therein, focusing on its day-to-day variability and unobserved heterogeneity across individuals. It remains the case that the "central problem of action space research is that as yet there is no theory describing the relationship between these dimensions [pertaining aspects of action space] and the variables used" (Dangschat, et al, 1982, p. 1156). This study is an attempt to accumulate some basis for the construction of such a theory.

SECOND MOMENTS OF ACTIVITY LOCATIONS

The action space of an individual is represented in this study by the second moment of the out-of-home activity locations it contains. Let C be the centroid of the activity locations of an individual on a given day, and let I_C be the second moment of the activity locations about C, evaluated in terms of Euclidean distance. Also let I_H be the second moment of the centroid about the home location, i.e., $I_H = L^2$, where L is the distance between the home and the centroid (see Figure 1).

Let N be the number of activity locations. If N is 1, then $I_C = 0$ and $I_H = L^2$, where L in this case equals the length of the trip from the home to the activity location. If N is greater than 1, then I_C indicates how spread the activity locations are, and I_H indicates how far away from the home they collectively are. The total moment of the activity locations about the home is given as $I_C + I_H$. Thus I_C and I_H describe how far away from the home the center of activities locations is (I_H) and how spread the activity locations are around their center (I_C).

For example, suppose an individual engaged in activities at three locations on a given day as shown in Figure 2. These activity locations are situated at the coordinates shown in the figure. Their centroid has coordinates, $(X_C, Y_C) = (6.0,7.0)$, as computed in the figure, and the distance from the home location (L) is determined as 5 km. The second moment of the activity locations about their centroid is computed as the sum of the squared distances between the centroid and the respective activity locations. For an earlier application of second moments, see Dijst (1999).

Like any other method, the second moment as a method of representing action space has its advantages and disadvantages. For example, it does not represent the topology of an action space. Also, the second moment alone may misrepresent the spread of activity locations in urban space. For example, a second moment of 20 around the activity centroid may imply five activity locations, each 2 kilometers away from the centroid, or two locations each 3.16 $(=\sqrt{10})$ kilometers from the centroid (Figure 3). On the other hand, there are cases where the second moment is capable of distinguishing between actions spaces while other methods fail to do so as illustrated in Figure 4.

Despite these limitations, use of second moments offers the advantage in its simplicity that the expansion of action space can be represented by just two parameters, I_H and I_C, which are well defined and easy to compute. Its simplicity is an important advantage as it facilitates application of standard statistical methods. Note that the analysis of this study is concerned with *actual* action space, but not with *potential* action space or *predicted* reachable distance (Dijst, 1999; Schönfelder and Axhausen, 2003).

As noted earlier, the empirical analysis of this study is based on the *Mobidrive* data, which contain information from six-week continuous travel diaries. The survey was carried out with the aim to analyze the rhythms in the behavior of the respondents. In the data set, every activity location is geo-coded, facilitating accurate computation of second moments. In order to eliminate extraordinary second moment values, regional trips taken outside the city boundaries are excluded in this analysis. The database used in the analysis involves 32,539 person trips made by 261 sample individuals. Sample profiles can be found in Table 1.

SECOND MOMENTS OF ACTIVITY LOCATIONS

The distribution of second moments of activity location is discussed by employment status and residence area type in the following sub-section. Then, to examine what factors influence day-to-day variation in action space for each individual, the variance of second moments is analyzed using ordinary least square models. The second moment itself will be modeled with an individual specific error term using panel regression in the next section. All models reported in this paper are estimated with LIMDEP Version 8.0 by Econometric Software, Inc.

The Distribution of Second Moment Values

The mean and standard deviation of I_H and I_C are presented in Table 2 by day of the week and by employment status. They are summarized by residence area type in Table 3. Residence area is classified into three: central business district (CBD), inner city and suburbs.

As the worker and student tend to have fixed obligatory trips with fixed activity locations on weekdays, their total moment ($I_H + I_C$) is relatively stable on Mondays through Thursdays. On Fridays and Saturdays, when they are more oriented toward discretionary activities, activity locations become farther from home and more dispersed. Non-workers do not show clear tendencies in total moment values across weekdays and Saturdays. On Sundays, where stores are close in Germany, individuals tend to make fewer trips and visit fewer locations regardless of employment status. Consequently I_C takes on smaller values. The results here are consistent with those by Srivastava and Schönfelder (2003) who note “The full time workers have a highly stable activity space during the weekdays, but during the weekends they become highly unstable”.

Workers’ I_H based on work trips only are larger than those based on all trips on weekdays. The differences, however, are rather small. It can also be seen from Table 2 that workers’ I_H is much larger than those of students and non-workers. The results support the notion that a worker’s action space is defined primarily by their residential and work locations and other activities are located around those two locations (see Pred, 1977; Golledge and Stimpson, 1997). Overall, as work locations tend to be farther from the home base than non-work activity locations, workers have more expansive action space with dispersed activity locations. Djist (1999) in his study of two-earner families in Dutch communities also obtained this result.

Inner-city residents tend to have larger total moments than those in the other residence area types, especially on weekend days. On weekdays, the I_H of inner-city workers are similar to those of CBD workers, and their I_C values and the number of trips are higher. Likewise inner-city students and non-workers have larger I_C values. This may be because the inner-city area, which lies between the CBD and suburbs, has mixed opportunities for various activities, encouraging the residents to be more mobile.

CBD students and non-workers exhibit very small total moment values, implying that they make fewer and shorter trips to less spread locations. It may be the case that their needs are met by opportunities in their residential areas. The sample, however, is very small to be conclusive.

Analysis of the Variation in the Total Moment

It has been shown in the previous sub-section that the second moment of activity locations, evaluated at the level of the individual, takes on different values between weekdays and weekend days, probably reflecting different types of activities carried out on the two types of days. The analysis of this section addresses the longitudinal variation of the second moment across days of the same day of the week for a given individual over a six-week survey period. It is reasonable to assume that an individual tends to pursue similar types of activities on days of a given day of the week, and the variation in action space will be small. The analysis here focuses on factors that are associated with the variation thus defined.

Let the longitudinal variation of the total second moment on day of the week *d* be evaluated as the variance of the, up to six, second moment values observed for each individual. This variance is examined by least squares regression. Personal attributes used as explanatory variables are: sex, marital status, driver's license holding, age class, and employment status. Household attributes include: the number of household members, number of motor vehicles, frequency of telecommunications incidents (phone calls, fax transmissions, and e-mail messages), household income, presence of a dependent child (less than 15 years old), and residence area type.

The variance of the total moment for individual *i* is the dependent variable of the analysis. The model focuses on the variation within each individual and what factors influence it. Variances for the same individual but on different days of the week are treated as independent observations in this analysis. Let the model be

$$V_i^d = \beta' X_i^d + \varepsilon_i^d, \quad d = 1,2,...,7; \quad i = 1,2,...N \tag{1}$$

where *d* refers to the day of the week, *N* is the number of individuals in the sample, and

V_i^d = the variance of total moments for individual *i* on day of the week *d*, and
X_i = the vector of explanatory variables.

Estimation results are presented in Table 4. Overall, with the small coefficients of determination and with most explanatory variables insignificant, the models' fit is poor, suggesting that the extent of variations in the second moment is difficult to explain. Salient results may be summarized as follows:

- Variances are larger on weekend days than on weekdays. The variation in the total moment is particularly large on Fridays and Saturdays. This is presumably because individual are more oriented toward discretionary activities on weekend days than on weekdays. Srivastava and Schönfelder (2003) also show that the individual's activity space tends to be stable during weekdays and highly unstable during weekend days.
- On weekdays, age is negatively associated with the longitudinal variation of the second moment; older individuals tend to have less variable action spaces across days of a given day of the week.
- Driver's license holding is not associated with the longitudinal variation of the second moment, and the number of motor vehicles has a negative, but not significant (at α = 10%) effect on weekend days.
- The frequency of telecommunications connections is positively and significantly associated with the longitudinal variation of the second moment on weekdays.
- Inner-city residents have larger variations, both on weekdays and weekend days, than those in other area types. It may be the case that inner-city residents have greater access to activity opportunities, which makes it easier for them to travel and engage in activities,

which at the same time makes the longitudinal variation greater for each resident. The influence of residence area type is stronger on weekdays than on weekend days.

Overall, on weekdays when the individual's activities tend to be obligatory and routine, the explanatory variables that are associated with roles and commitments (sex, martial status and presence of a child) do not have significant influences on the longitudinal variation of the total moment. On the other hand, on weekend days, when activities are more discretionary and perhaps family-oriented for those who live with one, the presence of a dependent child tends to increase the longitudinal variation of the total moment. Workers have much larger variances on weekend days, probably reflecting the tendency that they engage in non-work activities at a variety of locations.

UNOBSERVED HETEROGENEITY IN DAY-TO-DAY VARIATION

In this section the values of the second moments themselves (I_H, I_C and $I_H + I_C$) are examined using linear regression models. To examine the effect of an individual-specific error component on second moment values, panel regression analysis is carried out. The general form of the model is:

$$Y_{it} = \beta' X_{it} + \alpha_i + \varepsilon_{it}, \quad i = 1, 2, \ldots N, \quad t = 1, 2, \ldots, T \qquad (2)$$

where *i* refers to the individual as before, *t* to the day, and

Y_{it} = moment value for individual *i* on day *t*,
X_{it} = a vector of explanatory variables,
α_i = individual-specific error term, and
ε_{it} = random error term (white noise).

This model includes unobserved heterogeneity across individuals, represented by the individual-specific error term, α_i, which varies across individuals but assumes a constant value from day to day for a given individual. All error components are assumed to be normally distributed, mutually independent, and serially uncorrelated. Results of model estimation are summarized in Tables 5 and 6.

The weekday results in Table 5 indicate:

- Except for the dummy variable, *Karlsruhe*, indicating that the individual resides in Karlsruhe, there are no significant explanatory variables (at α = 10%) that influence I_H. Employment status and vehicle availability show positive associations, but they are not significant.
- Individuals who live in Karlsruhe tend to have activity locations that are less spread and whose centroid is closer to the home location.
- The spread of activity locations (I_C) is influenced positively by driver's license holding, household income, residence area type, and the day being a Friday. As in earlier results, individuals who live in inner city or suburbs have more spread activity locations than those in CBD, and activity locations tend to be more spread on Fridays.
- Individuals from larger households have less spread activity locations on weekdays. This may be due to intra-household interactions such as task allocation which may reduce each member's activity engagement, leading to a compact action space.

Weekend results shown in Table 6 indicate:

- Contrary to the weekday results, the model for I_H has several significant explanatory variables. On the other hand, the only significant variable in the model for I_C is the *Saturday* dummy. The *worker* dummy and *inner city residence* dummy have positive coefficients, but not significant at α = 10%.
- On weekend days, I_H is influenced by household attributes including the number of household members, number of children, and number of motor vehicles. These variables are not at all significant in the weekday model for I_H. Residence area type and *Karlsruhe* dummy are also significant in the weekend model for I_H.
- Judging from the average values of I_C and I_H, the centroid of activity locations tends to be farther away from home and activities are more spread on weekend days than on weekdays.

Decomposing the Variation

To probe further into the nature of day-to-day variations in I_H and I_C, their variances are decomposed into systematic variations and random variations, which are respectively further decomposed into within-person variances and between-person variances, and individual specific error variances and white noise. Results can be seen in Tables 7 and 8.

Of the estimated total sum of squares, the regression sum of squares (SSR) account for only about 3 to 5%, and the rest is the error sum of squares (SSE). Of the regression sum of squares (SSR), for I_H and total moment, within-person variance is less than 4.4% and the rest is between-person variance. The corresponding values for I_C are 10.8% for weekdays and 22.7% for weekend. The spread of activity locations (I_C) and the centroid of activity locations (I_H) are rather difficult to systematically explain, especially on weekdays.

On weekdays, the heterogeneity term, or the individual-specific error term, accounts for about 53.5% of the error sum of squares for I_H, and 15.2% for I_C. The rest is white noise. That heterogeneity and white noise are a dominant part of the total sum of squares implies that there are many unaccounted factors influencing the second moments. On weekend days, only 3.1% to 7.2% of the square sum of errors is attributable to the heterogeneity term.

It is reasonable to assume that, for workers and students, activity locations on weekdays are influenced by the location of the work place or school to which they commute. This will lead to a stable second moment of the centroid of activity locations (I_H), which will be strongly influenced by the home-to-work or home-to-school distance. In this sense, it is not at all surprising that the heterogeneity term is a dominant component of the variance of I_H on weekdays. No such regularity can be anticipated for the spread of activities locations (I_C); the error sum of squares is dominated by white noise.

White noise is the dominant component in the results for weekend days. It has been shown in Tables 5 and 6 that the average moment values are appreciably larger, and their standard deviations are slightly larger on weekend days than on weekdays. Together these results constitute a piece of evidence that weekend travel is more flexible and not recurrent.

CONCLUSION

Using the *Mobidrive* data set, a six-week travel diary from Karlsruhe and Halle, Germany, this paper has examined the characteristics of action space and its day-to-day variation based on the representation of its extension by the second moment of activity locations it contains. The study has shown that the residence location, employment status and day of the week have significant influences on the second moments of activities locations. Inner-city residents have higher and more variable moment values than those who live in other areas. On Fridays and Saturdays the second moments tend to take on higher values and larger variations. Workers tend to have more stable moment values than non-workers and students. Moreover, workers tend to have more spread activity locations. Suburban non-workers exhibit little difference between weekdays and weekend days in terms of moment values.

The statistical analyses of the variation of the second moments have revealed that, on weekdays, the spread of activity locations (I_C) and the centroid of activity locations (I_H) tend to be stable from day to day. Moreover, the variability of I_H on weekdays is dominantly influenced by the heterogeneity across individuals, which presumably represents in this case the variability of work places, which are fixed for each individual but vary across individuals. On weekend days, the individual have more flexible patterns with more variations within each person, and unobserved heterogeneity only have minor effects on random variations.

Differences in activity orientation between weekdays and weekend days appear to explain the differences in travel patterns. On weekdays, when activities tend to be obligatory and routine, activity locations tend to be fixed, leaving little room for influences of the individual's attributes. On weekend days, when the activities tend to be more discretionary, activity locations are more variable and less predictable. The findings of this study are consistent with the hypotheses postulated earlier in this study.

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List of Tables and Figures

TABLE 1. The Profiles of the Sample Used in the Study

	N	%	Mean
Number of individuals	261		
Number of households	131		
Total number of reported days	8430		
Total number of reported trips	32539		
Individual Attributes			
Male [D]	142	54.41	
Married [D]	131	50.19	
Driver's license ownership [D]	167	63.98	
Less than 25 years old [D]	73	27.97	
25 - 34 years old [D]	32	12.26	
35 - 44 years old [D]	49	18.77	
45 - 54 years old [D]	36	13.79	
55 - 64 years old [D]	43	16.48	
65 years old or over [D]	28	10.73	
Status			
Worker [D]	110	42.15	
Student [D]	67	25.67	
Non-worker [D]	84	32.18	
Household Attributes			
Number of household members			2.84
Number of motor vehicles			1.29
Number of telecommunications connections			2.44
Family with child < 15 years old (dependent child) [D]	91	34.87	
Household income [x 1,000 DM]			4.36
Residential Area Type			
CBD Resident [D]	18	6.90	
Inner city Resident [D]	75	28.74	
Suburbs Resident [D]	168	64.37	
Karlsruhe Resident [D]	122	46.74	
Halle Resident [D]	139	53.26	
Trip Characteristics			
Average of number of trips per day			3.86
Average of number of visits per day			2.20
Average travel time expenditure per day			20.19
Average out-of-home activity time per day			432.69
Monday [D]	1308	15.52	
Tuesday [D]	1302	15.44	
Wednesday [D]	1288	15.28	
Thursday [D]	1317	15.62	
Friday [D]	1307	15.50	
Saturday [D]	1038	12.31	
Sunday [D]	870	10.32	

Note: [D] : Dummy Variable

TABLE 2. Second Moments of Activities Locations, by Employment Status

			Monday		Tuesday		Wednesday		Thursday		Friday		Saturday		Sunday		Average
			Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	
Workers (N = 110)	All trips	I_H	66.61	197.20	71.48	208.89	66.28	190.20	56.03	169.93	70.94	197.54	76.49	207.15	72.82	194.95	68.66
		I_C	43.97	140.81	34.44	110.21	34.32	113.43	51.86	139.65	65.41	171.09	68.05	184.71	26.92	91.77	46.42
		Σ	110.58	244.85	105.92	238.78	100.60	230.05	107.88	231.99	136.35	270.53	144.54	286.48	99.75	217.97	115.09
		NT	3.90		3.89		3.64		3.98		4.28		4.21		3.25		3.88
		NV	2.30		2.32		2.13		2.36		2.47		2.38		1.72		2.24
	Work Trips Only	I_H	79.97	213.28	94.09	239.66	86.24	222.94	77.14	211.09	97.15	234.52	73.77	223.38	19.12	41.95	75.35
		I_C	15.23	78.74	8.28	41.05	10.98	62.91	14.84	72.02	8.11	56.25	11.50	86.73	1.82	10.84	10.11
		Σ	95.20	227.15	102.37	242.07	97.22	232.32	91.98	223.32	105.26	242.66	85.26	240.15	20.94	43.28	85.46
		NV	1.42		1.47		1.33		1.39		1.27		0.41		0.28		1.14
Students (N = 67)		I_H	14.67	64.27	12.08	59.44	9.12	28.33	8.90	30.37	18.94	75.21	40.57	152.85	50.08	140.36	22.05
		I_C	27.98	122.74	15.49	72.05	17.19	86.66	19.68	93.83	36.89	127.36	35.53	112.04	29.96	96.99	26.10
		Σ	42.65	153.49	27.57	107.02	26.31	100.55	28.59	106.13	55.83	174.73	76.10	201.42	80.04	181.82	48.15
		NT	4.18		4.00		3.91		4.07		4.33		3.71		3.23		3.92
		NV	2.32		2.22		2.15		2.26		2.41		2.14		1.75		2.18
Non-workers (N = 84)		I_H	36.49	133.08	30.99	97.09	40.92	132.10	47.53	165.81	31.73	114.03	49.04	158.54	60.45	171.00	42.45
		I_C	36.31	119.33	34.04	125.60	27.71	105.24	33.72	111.73	41.93	134.74	28.85	105.41	12.79	61.06	30.76
		Σ	72.80	193.33	65.03	177.84	68.62	182.00	81.25	209.21	73.66	197.87	77.89	209.14	73.24	187.01	73.21
		NT	3.91		3.78		3.84		3.88		4.01		3.38		2.80		3.66
		NV	2.19		2.11		2.18		2.26		2.26		1.89		1.49		2.05

Note: I_H and I_C value x 10^6

NT = Average number of trips per person per day

NV = Average number of visits per person per day

TABLE 3. Second Moments of Activity Locations, by Residence Area Type and Employment Status

			Monday		Tuesday		Wednesday		Thursday		Friday		Saturday		Sunday		Average
			Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	
Workers	CBD Residents (N = 12)	I_H	81.24	222.65	68.51	203.96	72.78	214.11	60.64	176.98	61.39	194.95	67.09	197.92	36.20	162.10	63.98
		I_C	15.07	61.81	38.55	134.48	57.53	162.59	51.85	158.05	26.06	86.25	83.42	225.40	24.21	120.50	42.38
		Σ	96.31	236.27	107.06	251.40	130.31	286.04	112.49	256.38	87.45	218.11	150.51	303.96	60.41	202.59	106.36
		NT	4.05		4.32		3.78		4.24		4.44		4.65		3.16		4.09
		NV	2.54		2.72		2.35		2.58		2.78		2.84		1.77		2.51
	Inner city Residents (N = 29)	I_H	69.67	213.70	73.66	215.50	70.95	215.64	74.72	220.04	92.17	241.42	106.89	270.83	77.26	210.76	80.76
		I_C	50.27	164.15	53.62	146.31	44.20	133.65	56.52	149.66	98.28	235.13	93.11	216.21	28.95	86.07	60.71
		Σ	119.94	271.07	127.28	266.75	115.15	262.97	131.24	275.00	190.45	340.33	200.00	351.53	106.21	230.45	141.47
		NT	4.14		4.29		3.99		4.25		4.64		4.82		3.56		4.24
		NV	2.47		2.67		2.35		2.62		2.72		2.78		1.98		2.51
	Suburban Residents (N = 69)	I_H	62.95	185.91	71.06	207.49	63.21	174.42	47.58	142.97	64.08	177.30	66.06	177.08	75.61	192.22	64.36
		I_C	46.16	139.61	25.79	84.84	26.24	91.55	49.95	132.22	59.23	148.69	55.51	161.70	26.44	90.31	41.33
		Σ	109.11	235.36	96.86	224.10	89.45	203.07	97.53	207.03	123.32	243.37	121.57	250.64	102.05	214.91	105.70
		NT	3.77		3.65		3.47		3.82		4.10		3.88		3.14		3.69
		NV	2.18		2.11		1.99		2.22		2.32		2.14		1.60		2.08
Students	CBD Residents (N = 3)	I_H	3.80	5.70	3.03	5.17	10.44	19.35	6.63	15.51	2.53	4.47	1.84	3.25	33.59	60.68	8.84
		I_C	0.82	2.04	0.60	2.03	9.98	26.17	0.01	0.03	1.49	2.41	5.91	8.10	3.94	9.64	3.25
		Σ	4.62	5.60	3.63	5.51	20.41	43.77	6.64	15.51	4.02	4.34	7.75	7.74	37.53	60.05	12.09
		NT	3.36		2.93		2.71		2.75		3.85		3.40		2.83		3.12
		NV	1.71		1.50		1.36		1.33		2.00		1.80		1.33		1.58
	Inner city Residents (N = 18)	I_H	23.63	102.39	20.01	100.89	14.46	29.99	12.84	29.12	51.53	135.34	60.86	193.03	52.81	167.23	33.73
		I_C	47.52	178.75	14.83	76.09	28.83	134.33	54.03	174.92	80.09	193.69	64.15	179.48	21.55	87.42	44.43
		Σ	71.15	219.35	34.83	131.04	43.29	151.39	66.87	191.29	131.61	281.04	125.01	275.01	74.36	212.03	78.16
		NT	3.85		3.39		3.45		3.88		4.26		3.82		3.37		3.72
		NV	2.25		1.81		1.90		2.29		2.51		2.29		1.86		2.13
	Suburban Residents (N = 46)	I_H	11.68	42.28	9.47	33.24	7.06	27.96	7.50	31.32	6.97	21.03	34.88	139.11	49.97	135.31	18.22
		I_C	21.67	94.81	16.61	72.55	13.28	63.10	7.46	18.32	21.76	88.24	26.83	78.34	33.07	100.99	20.10
		Σ	33.35	121.12	26.08	99.29	20.34	75.90	14.96	37.61	28.73	100.80	61.71	171.01	83.04	176.75	38.32
		NT	4.37		4.32		4.17		4.22		4.39		3.69		3.20		4.05
		NV	2.39		2.42		2.29		2.31		2.40		2.10		1.73		2.24

TABLE 3. Second Moments of Activity Locations, by Residence Area Type and Employment Status (*Continued*)

			Monday		Tuesday		Wednesday		Thursday		Friday		Saturday		Sunday		Average
			Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	
Non-workers	CBD Residents (N = 3)	I_H	1.73	2.62	5.30	12.22	29.17	89.89	2.25	3.36	4.17	7.78	4.54	5.29	2.12	3.40	7.04
		I_C	3.51	6.94	0.67	1.87	9.72	23.21	3.96	5.82	8.03	13.15	28.79	78.82	0.89	1.78	7.94
		Σ	5.24	9.18	5.97	12.25	38.89	112.28	6.21	8.81	12.20	16.41	33.33	83.26	3.02	3.57	14.98
		NT	4.12		4.08		3.94		4.08		4.34		3.86		3.12		3.93
		NV	2.38		2.38		2.28		2.39		2.50		2.20		1.65		2.25
	Inner City Citizen (N = 28)	I_H	35.27	144.71	23.74	66.20	33.58	136.20	50.38	165.28	23.36	61.56	67.87	187.65	47.06	173.25	40.18
		I_C	35.48	138.49	55.34	180.01	26.61	113.11	46.90	148.95	61.85	181.70	44.68	146.68	26.33	96.87	42.46
		Σ	70.76	218.44	79.07	219.29	60.20	198.14	97.28	239.41	85.22	217.66	112.55	266.15	73.39	215.05	82.64
		NT	4.16		4.16		4.10		4.07		4.62		3.54		3.13		3.97
		NV	2.36		2.37		2.32		2.30		2.63		1.96		1.67		2.23
	Suburban Residents (N = 53)	I_H	38.69	130.37	35.56	110.76	44.94	132.36	48.69	170.81	37.22	134.62	42.60	146.95	69.40	171.90	45.30
		I_C	38.23	111.99	24.40	87.26	29.20	104.39	28.64	89.96	33.74	107.10	21.75	81.28	5.74	25.14	25.96
		Σ	76.92	184.62	59.96	155.81	74.14	177.52	77.34	197.57	70.96	192.11	64.35	180.90	75.15	172.93	71.26
		NT	3.76		3.57		3.69		3.76		3.67		3.27		2.61		3.48
		NV	2.09		1.97		2.09		2.23		2.05		1.83		1.39		1.95

Note : I_H and I_C value x 10^6 NT = Average number of trips per person per day NV = Average number of visits per person per day

TABLE 4. Longitudinal Variation of the Individual's Total Moment

	Weekday		Weekend	
	Coeff.	t-ratio	Coeff.	t-ratio
Constant	-10.26	-0.64	-42.66	-1.18
Male [D]	-3.47	-0.85	-9.03	-0.99
Married [D]	-1.28	-0.22	-15.28	-1.21
Driver's license ownership [D]	3.84	0.68	0.07	0.01
Less than 25 years old [D]	-4.56	-0.42	29.48	1.24
25 - 34 years old [D]	10.77	1.25	40.85	2.12
35 - 44 years old [D]	-18.87	-2.57	4.99	0.32
55 - 64 years old [D]	-21.42	-2.90	21.92	1.34
65 years old or over [D]	-39.44	-4.37	5.94	0.30
Number of household members	-6.23	-2.03	1.09	0.16
Number of motor vehicles	-0.0002	-0.01	-0.05	-1.43
Number of telecommunications connections	2.32	1.93	-0.80	-0.30
Family with dependent child [D]	-3.58	-0.56	28.48	2.06
Household income [x 1,000 DM]	2.54	2.02	-2.77	-0.98
Inner city [D]	44.35	5.29	51.21	2.55
Suburbs [D]	24.72	3.05	24.09	1.23
Worker [D]	10.36	1.00	59.11	2.64
Non-worker [D]	28.21	2.65	44.88	1.93
Monday [D]	6.66	1.11		
Tuesday [D]	-0.84	-0.14		
Thursday [D]	7.73	1.29		
Friday [D]	17.07	2.85		
Saturday [D]			20.98	2.50
Mean of dependent variable value	24.20		43.40	
Standard deviation	69.61		92.19	
Number of observations	1258		456	
Degrees of freedom	21	1236	18	437
F	5.37		2.58	
Residuals sum of squares	5581053		3495235	
R^2	0.0837		0.0959	
Adjusted R^2	0.0681		0.0587	

TABLE 5. Models of Second Moments: Weekdays

	I_H		I_C		Total Moment	
	Coeff.	t-ratio	Coeff.	t-ratio	Coeff.	t-ratio
Constant	-1.931	-0.40	0.280	0.12	-1.626	-0.27
Male [D]	0.766	0.49	-0.283	-0.37	0.497	0.25
25 - 34 years old [D]	-0.462	-0.11	2.433	1.20	2.058	0.40
35 - 44 years old [D]	2.719	0.66	1.224	0.60	3.962	0.77
45 - 54 years old [D]	1.643	0.38	-0.667	-0.32	0.969	0.18
55 - 64 years old [D]	1.204	0.28	0.459	0.22	1.603	0.30
65 years old or over [D]	1.069	0.22	-1.677	-0.71	-0.661	-0.11
Married [D]	-2.170	-0.98	-0.286	-0.26	-2.461	-0.90
Driver's license ownership [D]	1.274	0.57	2.207	2.00	3.452	1.24
Number of household members	-0.411	-0.33	-1.317	-2.16	-1.747	-1.14
Number of motor vehicles	1.501	1.10	0.060	0.09	1.565	0.92
Number of telecommunications connections	0.251	0.47	0.204	0.77	0.445	0.67
Family with dependent child [D]	0.88	0.35	0.07	0.06	0.95	0.31
Household income [x 1,000 DM]	0.302	0.61	0.547	2.24	0.858	1.39
Worker [D]	4.312	1.05	-1.197	-0.60	3.117	0.61
Non-worker [D]	3.276	0.78	-1.129	-0.55	2.146	0.41
Inner city [D]	1.166	0.35	4.699	2.86	5.910	1.43
Suburbs [D]	1.340	0.42	3.059	1.95	4.412	1.12
Karlsruhe [D]	-3.726	-2.27	-1.263	-1.57	-4.983	-2.46
Monday [D]	-0.061	-0.17	0.798	1.85	0.727	1.29
Tuesday [D]	-0.202	-0.55	0.142	0.33	-0.065	-0.12
Thursday [D]	-0.401	-1.09	0.956	2.21	0.560	0.99
Friday [D]	0.090	0.24	2.272	5.25	2.364	4.19
Number of observations	6407		6407		6407	
Mean of dependent variable value	4.313		3.598		7.911	
Degrees of freedom	22	6384	22	6384	22	6384
F	14.74		11.04		17.24	
SD of dependent variable	15.01		12.29		20.48	
Var[α]	128		27		194	
Var[ε]	100		123		226	

TABLE 6. Models of Second Moments: Weekend

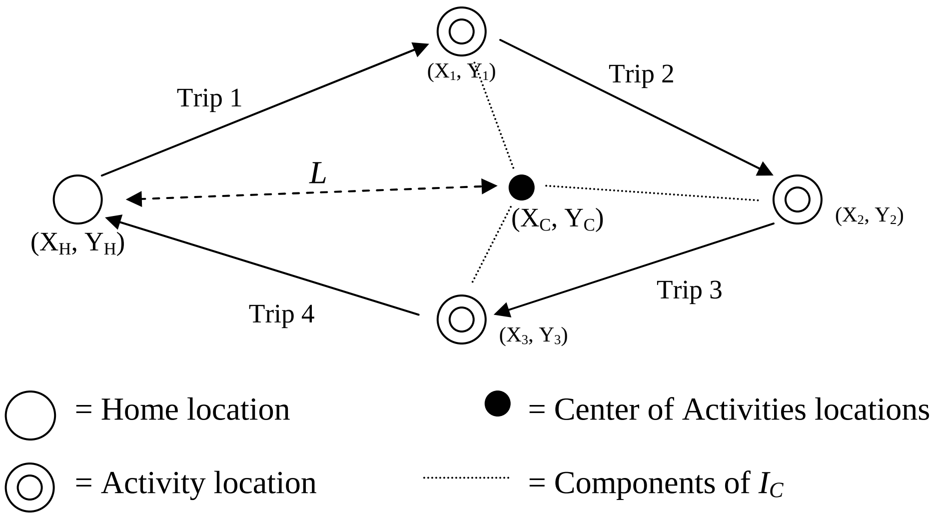
	I_H		I_C		Total Moment	
	Coeff.	t-ratio	Coeff.	t-ratio	Coeff.	t-ratio
Constant	2.802	0.89	-0.501	-0.18	2.201	0.52
Male [D]	-0.264	-0.27	-0.063	-0.07	-0.308	-0.23
25 - 34 years old [D]	5.503	2.25	2.569	1.18	7.981	2.41
35 - 44 years old [D]	1.918	0.79	-2.393	-1.11	-0.592	-0.18
45 - 54 years old [D]	1.935	0.77	-3.016	-1.34	-1.250	-0.37
55 - 64 years old [D]	3.221	1.22	-1.173	-0.50	1.925	0.54
65 years old or over [D]	1.431	0.48	-0.798	-0.30	0.509	0.13
Married [D]	-1.854	-1.31	-0.450	-0.36	-2.158	-1.12
Driver's license ownership [D]	-2.053	-1.39	0.058	0.04	-2.010	-1.01
Number of household members	-1.625	-2.07	-0.264	-0.38	-1.917	-1.80
Number of motor vehicles	1.376	1.60	-0.001	0.00	1.370	1.17
Number of telecommunications connections	-0.314	-0.86	0.451	1.39	0.148	0.30
Family with dependent child [D]	2.57	1.74	1.35	1.03	3.94	1.97
Household income [x 1,000 DM]	0.423	1.39	-0.168	-0.62	0.264	0.64
Worker [D]	1.430	0.58	3.524	1.61	4.989	1.50
Non-worker [D]	0.702	0.28	0.840	0.37	1.578	0.46
Inner city [D]	4.794	2.08	3.081	1.51	7.981	2.56
Suburbs [D]	5.694	2.55	1.627	0.82	7.458	2.46
Karlsruhe [D]	-2.723	-2.77	-0.083	-0.09	-2.808	-2.11
Saturday [D]	-1.111	-1.44	2.789	4.79	1.689	1.65
Number of observations	1692		1692		1692	
Mean of dependent variable value	5.407		3.767		9.174	
Degrees of freedom	19	1672	19	1672	19	1672
F	2.32		4.70		3.73	
SD of dependent variable	16.08		12.66		21.62	
Var[α]	10		14		21	
Var[ε]	247		143		437	

TABLE 7. Analysis of Variance of the Second Moment of Activity Locations: Weekdays

		I_H			I_C			Total Moment		
		SS	%		SS	%		SS	%	
SSR	Within-person	189	0.3	0.01	4,144	10.8	0.4	4,919	3.1	0.2
	Between-person	68,160	99.7	4.7	34,405	89.2	3.6	151,437	96.9	5.6
	Subtotal	68,349	100	4.7	38,549	100	4.0	156,356	100	5.8
SSE	Individual Specific Error	734,868	53.5	50.9	141,689	15.2	14.6	1,083,810	42.8	40.3
	White Noise	639,852	46.5	44.3	787,481	84.8	81.4	1,446,319	57.2	53.8
	Subtotal	1,374,720	100	95.3	929,171	100	96.0	2,530,129	100	94.2
	Total	1,443,069		100	967,720		100	2,686,484		100

TABLE 8. Analysis of Variance of the Second Moment of Activity Locations: Weekend

		I_H			I_C			Total Moment		
		SS	%		SS	%		SS	%	
SSR	Within-person	494	4.4	0.11	3,114	22.7	1.1	1,141	3.5	0.1
	Between-person	10,793	95.6	2.5	10,581	77.3	3.9	31,082	96.5	3.9
	Subtotal	11,287	100	2.6	13,695	100	5.1	32,223	100	4.1
SSE	Individual Specific Error	13,188	3.1	3.0	18,593	7.2	6.9	26,829	3.5	3.4
	White Noise	412,830	96.9	94.4	238,871	92.8	88.1	731,247	96.5	92.5
	Subtotal	426,018	100	97.4	257,464	100	94.9	758,076	100	95.9
	Total	437,305		100	271,159		100	790,299		100

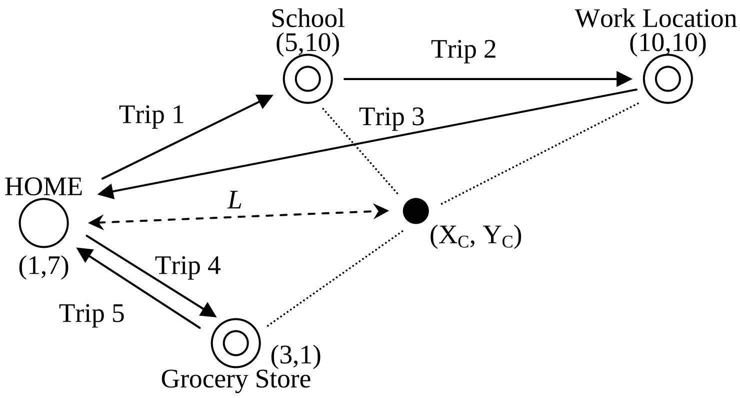


$$I_H = L^2 = (X_H - X_C)^2 + (Y_H - Y_C)^2,\ X_C = \frac{1}{3}\sum_{i=1}^{3} X_i \text{ and } Y_C = \frac{1}{3}\sum_{i=1}^{3} Y_i$$

$$I_C = \sum_{i=1}^{3}\left\{(X_i - X_C)^2 + (Y_i - Y_C)^2\right\}$$

FIGURE 1. Second Moment of Activity Locations

<u>Illustration Case</u>: Suppose on a given day an individual engaged in three out-of-home activities: dropping off his child at school, working at the office, and grocery shopping, and suppose he had the trip pattern shown below.



The location of the centroid of his activity locations has the coordinates:

$$X_C = \frac{5+10+3}{3} = 6;\ Y_C = \frac{10+10+1}{3} = 7,$$

With

$$L = \sqrt{(X_H - X_C)^2 + (Y_H - Y_C)^2} = \sqrt{(1-6)^2 + (7-7)^2} = \sqrt{25} = 5,$$

the elements of the second moment are given as:

$$I_H = L^2 = 5^2 = 25 \text{ and } I_C = \left\{\left((-1)^2 + 3^2\right) + \left(4^2 + 3^2\right) + \left((-3)^2 + (-6)^2\right)\right\} = 80.$$

The total second moment is given as $I_H + I_C = 25 + 80 = 105$

FIGURE 2. Second Moment of Activity Locations: Numerical Illustration

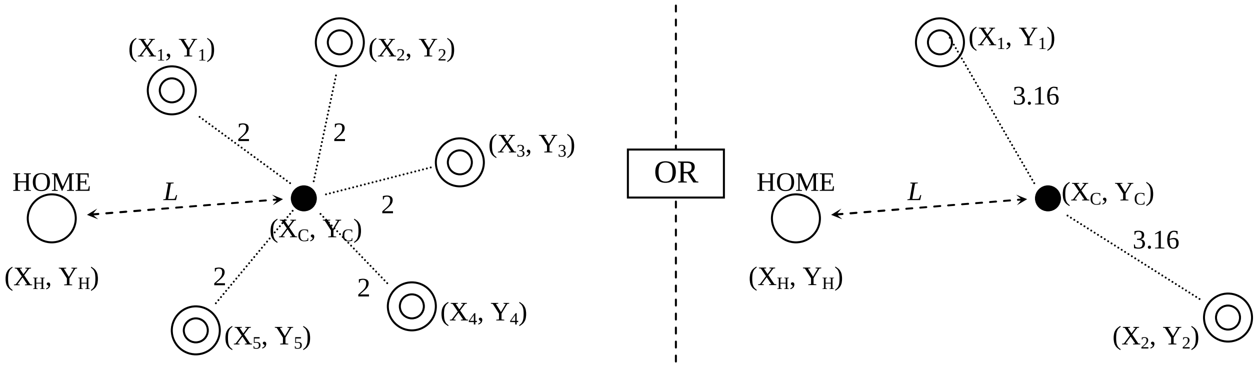


FIGURE 3. Two Sets of Activity Locations with Identical Second Moments

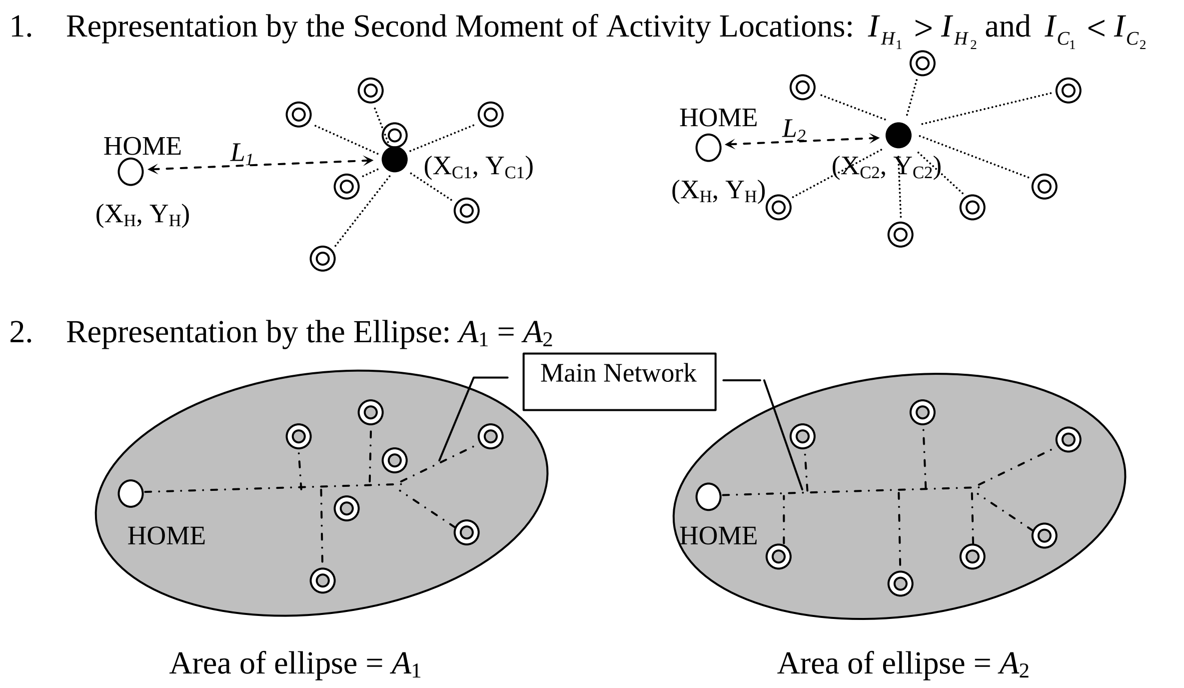


FIGURE 4. A Comparison of Different Approaches of Action Space Representation