Assessing patterns of spatial behavior in health studies: Their socio-demographic determinants and associations with transportation modes (the RECORD Cohort Study)

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Abstract

Prior epidemiological studies have mainly focused on local residential neighborhoods to assess environmental exposures. However, individual spatial behavior may modify residential neighborhood influences, with weaker health effects expected for mobile populations. By examining individual patterns of daily mobility and associated socio-demographic profiles and transportation modes, this article seeks to develop innovative methods to account for daily mobility in health studies. We used data from the RECORD Cohort Study collected in 2011-2012 in the Paris metropolitan area, France. A sample of 2062 individuals was investigated. Participants' perceived residential neighborhood boundaries and regular activity locations were geocoded using the VERITAS application. Twenty-four indicators were created to qualify individual space-time patterns, using spatial analysis methods and a geographic information system. Three domains of indicators were considered: lifestyle indicators, indicators related to the geometry of the activity space, and indicators related to the importance of the residential neighborhood in the overall activity space. Principal component analysis was used to identify main dimensions of spatial behavior. Multilevel linear regression was used to determine which individual characteristics were associated with each spatial behavior dimension. The factor analysis generated five dimensions of spatial behavior: importance of the residential neighborhood in the activity space, volume of activities, and size, eccentricity, and specialization of the activity space. Age, socioeconomic status, and location of the household in the region were the main predictors of daily mobility patterns. Activity spaces of small sizes centered on the residential neighborhood and implying a large volume of activities were associated with walking and/or biking as a transportation mode. Examination of patterns of spatial behavior by individual socio-demographic characteristics and in relation to transportation modes is useful to identify populations with specific mobility/accessibility needs

and has implications for investigating transportation-related physical activity and assessing environmental exposures and their effects on health.

Keywords: Paris (France), spatial behavior, mobility, socioeconomic status, spatial analysis, principal component analysis.

Research highlights

- The spatial scale of our daily lives is not limited to the residential neighborhood.
- Spatial behavior was qualified and quantified by five structuring dimensions.
- Age, SES, and location of the residence were strong predictors of spatial behavior.
- Active and motorized travel modes were related to mobility pattern characteristics.

Introduction

Over the past decades, research on geographic life environments and health has first relied on residential administrative area subdivisions to estimate environmental exposure. Later ego-centered areas of exposure have been used, through circular (Berke et al., 2007; Seliske et al., 2009) or street network (Karusisi et al., 2013; Leal & Chaix, 2011) buffers of various sizes centered on individual residences. As a distinct issue than the so-called Modifiable Area Unit Problem related to the influence of the territory subdivisions used on the estimated statistics and associations (Mobley & Andrews, 2008; Openshaw, 1983), numerous critics were formulated against the traditional assessment of environmental exposures in neighborhood and health studies (Chaix et al., 2009). Scholars have pointed to the local trap (i.e., exclusive focus on local environments) (Cummins, 2007), to the residential trap (i.e., exclusive focus on residential neighborhoods) (Chaix et al., 2009), or to the uncertain geographic context problem (or difficulties to identify the truly relevant contexts) (Kwan, 2012a, b), all of which have potential for exposure misclassification.

Most people are highly mobile (Matthews, 2008), which underlines the need for innovative research strategies that can account for individual space-time behaviors in health studies (Lee et al., 2008; Perchoux et al., 2013). Concepts of spatial polygamy (Matthews, 2011; Matthews & Yang, 2013), network of usual places (Flamm & Kaufmann, 2006), and, more largely, activity space (Golledge & Stimson, 1997) are increasingly used. They guide our thinking on how environmental effects may act beyond the residential neighborhood. Furthermore, investigating individual spatial behavior may also shed light on the determinants and circumstances of active transport and transportation physical activity.

Daily mobility is increasingly accounted for in the assessment of neighborhood effects on health in emerging social/spatial epidemiology and health geography (Chaix et al., 2012;

Inagami et al., 2007; Kestens et al., 2012; Kestens et al., 2010; Mason, 2010; Setton et al., 2011; Vallée et al., 2010; Vallée et al., 2011; Vallée & Chauvin, 2012; Zenk et al., 2011). For instance, Inagami and colleagues examined associations between non-residential exposures and self-rated health (Inagami et al., 2007) and reported that non-residential exposures may confound and suppress residential neighborhood effects on health. Setton et al. observed that using solely residence-based exposures underestimated the true exposure to air pollution and biased towards the null the effect of air pollution on health (Setton et al., 2011). In their assessment of residential and non-residential foodscape exposure, Kestens et al. reported that activity space exposure significantly differed from the traditional residential exposure and that these differences varied according to age and socioeconomic status (Kestens et al., 2010). Vallée et al. found an interaction between the self-reported activity space and the residential density of health services on health seeking behaviors; woman living in a low health services density neighborhood were more likely to delay medical screening if their self-reported activity space was centered on their residential neighborhood (Vallée & Chauvin, 2012).

Time geography and transportation research have provided relevant frameworks and analytic tools to study spatial behavior. Various geographic measures of activity space have been proposed, including the standard deviational ellipse (Arcury et al., 2005; Rai et al., 2007; Schönfelder & Axhausen, 2003; Sherman et al., 2005; Yuill, 1971), the convex hull (Buliung & Kanaroglou, 2006a; Buliung et al., 2008), the daily or shortest path area connecting the locations visited (Schönfelder & Axhausen, 2003, 2004b) and kernel density surfaces (Kestens et al., 2010; Schönfelder & Axhausen, 2003, 2004a). These studies that have examined the association between individual socio-demographic characteristics and activity space metrics have shown that age (Fobker & Grotz, 2006; Lord et al., 2009), being a female (Lord et al., 2009), being a part-time worker (Dijst, 1999a, b), and having a residential location near the city center (Schönfelder & Axhausen, 2002) were associated with limited activity spaces in terms of extent and number of activity locations (Dijst, 1999a, b; Lord et al., 2009; Schönfelder & Axhausen, 2003).

Given the limited work on these questions, the present study seeks to refine the description of daily mobility patterns by proposing a set of spatial indicators based on individual-level data of networks of usual places. We further use these spatial indicators to establish a typology of mobility patterns, and evaluate which individual socio-demographic characteristics and active and motorized transportation modes were associated. Such analyses are potentially important for health research because daily mobility patterns need to be accounted for to improve our assessment of environmental influences.

The following hypotheses were tested in the present study: i) spatial behavior (or daily mobility habits) cannot be reduced to one variable (such as the number of trips) or one unique dimension but needs to be captured using a larger set of indicators, ii) spatial behavior is a multidimensional construct organized around a reduced number of conceptual axes that can be identified from a larger number of raw variables, iii) age, socioeconomic status, and location of the household within the region are related to daily mobility patterns, and iv) active modes of transportation are more often used when activity spaces are smaller and overlap the residential neighborhood.

Materials and methods

Population

This study relies on data of the second wave of the RECORD Study (Residential Environment and CORonary heart Disease). Some 2,312 adult participants were surveyed between February 2011 and March 2012. Among those, 1,029 participants had already been enrolled in the RECORD Study in the first wave (2007-2008) and 1,033 were new recruits. All participants were recruited without *a priori* sampling during a 2-hour preventive medical checkup conducted by the Centre d'Investigations Préventives et Cliniques (IPC) in four centers of the Paris Ile-de-France region. The entire data collection protocol was approved by the French Data Protection Authority. For further details on the recruitment procedure and RECORD Study, see (Chaix et al., 2011a; Chaix et al., 2011b).

Measures

Individual variables

As explanatory variables, the following individual characteristics were considered in our analysis: sex, age, citizenship (French or other), marital status (living alone or living in a couple), education (4 categories: no education and primary education, lower secondary education, higher secondary education and lower tertiary education, and upper tertiary education), tertiles of household income per consumption units (1125 and 1750 Euros/month), employment status (4 categories: stable job, unstable and precarious job, unemployed, and other), a score of material ownership (low, middle, or high), and the location of the household in the Paris Ile-de-France region (Paris, inner suburbs, and outer suburbs).

Individual perceptions of mobility and spatial behavior were measured using a self-administered questionnaire with the following items: systematic use of the nearest shops, traveling out of one's residential neighborhood perceived as a way to access new types of activities and shops, and traveling out of one's residential neighborhood considered as a waste of time, with possible answers fully agree, somewhat agree, somewhat disagree, and fully disagree, recoded into dichotomous agree / disagree.

Regarding their transportation mode, the participants also reported the usual number of days per week i) they walked at least 5 minutes at a time, ii) they cycled at least 5 minutes at a time, iii) they used public transports, and iv) they used a car.

Measures of spatial behavior

Participants were surveyed on their regular activity places and residential neighborhood using the VERITAS application (Visualization and Evaluation of Route Itineraries, Travel Destinations, and Activity Spaces) (Chaix et al., 2012). The VERITAS application is web based interactive mapping questionnaire administered during a face-to-face meeting with the participants. As described in details elsewhere (Chaix et al., 2012), the application allows participants to draw the perceived boundaries of their residential neighborhood on an electronic map, and precisely locate their regular activity locations. Information on frequencies of visit was further collected. The following activity places were surveyed: place of residence, secondary or alternative residences, workplaces, supermarkets, outdoor markets, bakeries, butcher shops, fruit and vegetable shops, fish stores, cheese merchants, other specialized food stores, tobacco shops, banks, post offices, hair salons/barbers, transportation stations used from the residence, sports facilities, entertainment facilities, places for cultural activities, places for community or spiritual activities, places where participants took relatives, and where they visited people. For most activity types, the participants were invited to report the destinations they visited at least once a week, without specific recall period. As exceptions to the once-a-week minimum frequency, participants were asked to geolocate workplaces where they spent at least one third of their working time; supermarkets they visited at least once a month; and regardless of frequency of use, their bank, post office, and hair salon/barber.

Using this spatial information, we defined three categories of indicators to qualify and quantify mobility patterns: i) lifestyle indicators related to the number of places visited and to the specialization of the activity space (the type of places visited), ii) geometric indicators of the activity space that reflect the shape and the scale of the activity space, and iii) indicators on
Figure 1 the importance of the residential neighborhood in the overall activity space that proxy the proportion of time spent in the immediate vicinity of the residence rather than elsewhere. Regarding the geometry of the activity space, a geographic information system was used to

derive convex hulls (Figure 1a), standard deviational ellipses (Figure 1b), and shortest paths between the residence and all activity locations (Figure 1c). Street network distances between the residence and activity locations were computed with street network data from the National Geographic Institute for activity places located in the Ile-de-France region. Indicators related to the residential neighborhood were computed with both the perceived residential neighborhood (PRN) and a 500m street network buffer centered on participant's residence. The measurement approach, definition, and bibliographic references are provided for all 24 indicators in Table 1.

Statistical analysis

In order to identify the main dimensions of spatial behavior, we first conducted a principal component analysis (PCA) on the 24 indicators, using a varimax rotation. A five-factor solution was selected based on Eigenvalues greater than 1. Then, the association between each of the five identified components of spatial behavior and individual demographics, socioeconomic status, perception of mobility, and location of the household in the region were estimated through multilevel linear modeling with random effects at the municipality level. Only the variables that were independently associated with each outcome were retained in the final models, with systematic adjustment for age and sex. We report the Intraclass Correlation Coefficient (ICC) – the proportion of the total residual variability that is at the municipality level and the Akaike Information Criterion (AIC) for the null models and the final models.

Finally, we assessed the relationship between each of the five spatial behavior dimensions and the number of days the participants used each transportation mode. PCA factor scores were divided in tertiles and average by transportation mode were computed. Trends were tested using the Jonckheere-Terpstra nonparametric trend test. All analyses were conducted with SAS, version 9.2.

Results

Description of the study sample

In the initial sample, 352 participants reported at least one activity place outside the Ile-de-France region, of which 66 reported at least one activity place outside the crown of counties bordering the Paris Ile-de-France region, including 19 who reported a regular activity location outside the country. These participants include 19 persons who located their primary residence outside the Paris Ile-de-France region and 162 participants who reported going regularly to a secondary home. As the general objective of this study was to describe the local spatial mobility patterns of individuals living in the Paris Ile-de-France region, we only retained participants residing in Ile-de-France and we excluded participants reporting at least one regular activity location outside the Paris Ile-de-France region and the crown of counties bordering the region. We also excluded participants with secondary homes (within or outside Ile-de-France), considering that commuting from principal to secondary homes was not part of local daily mobility and because participants often declared activity locations nearby their secondary home. Finally, one participant for whom no activity location at all was reported was excluded. The final sample thus comprises 2,062 individuals and 22,799 reported activity places with a mean of 11 activity places per individual (range: 2-52). The mean age of the participants was
Table 2 51 years (range: 33-84). The final sample was predominantly male (69%), French (83%), and with a stable employment (50%). Table 2 presents the characteristics of these participants.

Principal component analysis

Table 3

Results of the PCA are shown in Table 3. The five components that were retained explained 90% of the variance.

Component 1 explained 35% of the variation. Variables with highest factor loadings were the percentage of visits made in the PRN, the proportion of the overall activity/perceived space covered by the PRN, and the proportion of the activity space covered by the PRN. This component thus captures the proportion of activity pursued in the PRN and the importance of the residential neighborhood in the overall activity space. We labeled this component: “Centering of the activity space on the residential neighborhood.”

Component 2 - explaining 20% of the variance - was mainly characterized by the surface and the perimeter of the convex hull and by the maximum distance between the residence and an activity place. This component was labeled “Size of the activity space”.

The number of activity places and the number of visits made per week to places loaded strongly on component 3 which explained 16% of the variation. This component was identified as the “Volume of activities.”

Component 4 explained 10% of the variation in spatial behavior. This component captured the opposition between people who had a high share of their activities devoted to visiting local food stores and other services located in their residential neighborhood and people who, on the opposite, were more involved in recreational and social activities at more distant places from their residence. This component was labeled “Specialization of the activity space.”

Finally, component 5 explained 9% of the variation in spatial behavior. The shape of the activity space (Gravelius compactness coefficient and major to minor axis ratio) loaded heavily on this component, which expresses the stretching of the activity space and was thus labeled: “Elongation of the activity space.”

Multilevel analysis

Table 4

Table 4 presents the results of the five multilevel linear regressions. ‘Living alone’ and ‘considering that traveling out of the residential neighborhood is a waste of time’ were not associated with any of the outcomes.

Component 1, or the degree of centering of the activity space on the residential neighborhood was associated with age, employment status, financial strain, systematic use of the nearest shop, willingness to travel out of the residential neighborhood, and the location of the household in the region. The activity space of older participants was more centered on their residential neighborhood. Individuals with an unstable employment status or without job tended to cluster their activity locations to a larger extent in their residential neighborhood. Individuals reporting financial strain had an activity space that was less centered on their residential neighborhood. Individuals who expressed the general willingness to use the nearest shops from their home were more likely to have activities clustered in their residential neighborhood. In contrast, individuals who consider that going outside their neighborhood provides access to other types of activities, had an activity space that was less centered on their neighborhood. Finally, an urban-suburban effect was noted: people living far from the city center had, to a greater extent, their activity places located outside their residential neighborhood.

Regarding the second dimension, males had a larger activity space than females, whereas unemployed participants or participants with a precarious job (compared to employed participants), a lower ownership score, and the systematic use of nearby shops were associated with a smaller activity space. Outer suburb residents were more likely to have a much larger activity space than residents of the city of Paris.

The “volume of activities” was lower among males, older people, non-French citizens, low educated individuals, unemployed participants, and participants with a precarious job. However, people reporting financial strain engaged in a higher volume of activities. Finally, living in the inner or outer suburbs was associated with a lower volume of activities than residing in the city of Paris.

Age, individual education, employment status, financial strain, systematic use of nearby shops, and location within the region were associated with the specialization of the activity space. Older participants had their activities more specialized towards the use of services (rather than other activities) nearby their residence. Similarly, people without a stable employment status and residents of the inner suburbs (compared to those of central Paris) had their activities in proportion more devoted to local food or other services and less to social and recreational activities.

Finally, individuals with a lower income had a more compact activity space. In contrast, participants with a permanent job had more elongated activity spaces than the unemployed or individuals with a precarious employment status.

In the null models, the ICC varied between 2.6% and 12.0%. The ICC was much lower in most cases after accounting for individual and contextual variables, which was to a large extent attributable to the difference in mobility behavior explained by living in Paris, in the inner suburb, or in the outer suburb.

Description of the use of transportation modes according to spatial behavior

Table 5 In descriptive analyses (Table 5), we found that walking and cycling were more common among participants whose activity space was centered on their residential neighborhood and who reported a higher volume of activity locations. Participants used public transportation more often when their activity space was more elongated, based on a higher volume of activity locations, and less specialized in food and other services. Finally, a larger and more elongated activity space, not centered on the residential neighborhood, and based on a lower volume of activities was associated with a higher average number of days of car use.

Discussion

Our work suggests that individuals' daily exposures are not bounded by their residential neighborhood. The main findings of the study are the following: i) spatial behavior is a multidimensional construct; ii) five structuring dimensions of spatial behavior were identified: the size of the activity space, the elongation of the activity space, the centering of the activity space on the residential neighborhood, the volume of activities, and the specialization of the activity space; iii) age, socioeconomic status, and the location of the household in the region were strong determinants of individual spatial behavior; and iv) the use of active transportation modes correlated strongly with small activity spaces comprising a high volume of activity places mainly located within the residential neighborhood.

The primary strength of the study is the large sample size and rich information on participants' activity places over a relatively large study territory that allowed the identification of diverse patterns of spatial behavior. Second, the combination of information on the PRN delimited by the participants themselves with a wide range of indicators obtained with a GIS from the activity locations of participants allowed us to characterize more accurately individual space-time behavior than in previous studies (Dijst, 1999b; Lord et al., 2009; Schönfelder & Axhausen, 2002). A third strength of the study is that the combination of PCA with regression analyses allowed to identify both patterns of spatial behavior and how these related to socio-demographic profiles. The fact that each of the five identified components of spatial behavior contributed to explain variations in the corresponding indicators confirms that spatial behavior is a multidimensional construct that cannot be reduced to a unique dimension.

However, there were limitations to our study. The main limitation is that the data on regular mobility were self-reported. Moreover, this exploratory study did not consider environmental factors in the multilevel linear regressions as independent variables to explain variations in the five identified dimensions of spatial behavior. Despite this limitation, the expected importance of the suburbia effect (Schönfelder & Axhausen, 2002) was accounted for in the present study by taking into account the location of the household in the Paris Ile-de-France region, which partly reflects differences in the accessibility to services and in the urban morphology. However, this methodological choice implies that effects of age, sex, and socioeconomic status were adjusted on the location of the household in the region, and should therefore be interpreted as direct effects net of the influence of these socio-demographic variables on the location in the region.

Finally, the present study did not account for the temporal dimension of spatial behavior, for which only minimal information was collected with VERITAS (frequency of visit). The RECORD GPS and MultiSensor Studies, based on a subsample of the participants wearing GPS for 7 days, are currently undergoing to overcome these limitations (Chaix et al., 2013a; Chaix et al., 2013b; Thierry et al., 2013).

Measuring the activity space

In order to focus on regular daily mobility, we excluded people regularly travelling (at least once a week) to a secondary residence, considering that a trip from the main residence to the secondary residence and travel patterns around the secondary residence are not part of daily mobility, which is often considered as centered on a daily basis on the main residence (Kaufmann, 1997). However, it must be kept in mind that this methodological choice likely results in the underestimation of the size of effective regular activity space of high socioeconomic status participants.

In order to describe spatial behavior, we relied on existing procedures to characterize the activity space, transforming point patterns into geographical forms. Despite their interest, the standard deviational ellipse and the convex hull are not ideal to represent the activity space.

Both of them capture large areas free of visited locations (Rai et al., 2007; Schönfelder & Axhausen, 2002) that may not be familiar to the participants. Therefore, these polygons are likely to be very rough approximations of the 'true' experienced space. For example, the standard deviational ellipse will tend to encompass the residence and the workplace that may be very distant from each other and a large portion of space between these locations that the individual never specifically visits (Schönfelder & Axhausen, 2002). In our analysis, the use of multiple geographical methods to represent the activity space likely mitigated the limitations of these specific indicators. Previous studies have suggested that the notion of "network of activity places" could more accurately reflect activity spaces (Chaix et al., 2012; Flamm & Kaufmann, 2006).

Our study did not develop indicators allowing to assess the polycentric or monocentric nature of the activity space (Flamm & Kaufmann, 2006; Perchoux et al., 2013; Schönfelder & Axhausen, 2004b; Vallée & Chauvin, 2012). It has been shown that individuals often tend to cluster their activities in a small number of subcenters due to the spatial distribution of resources (Schönfelder & Axhausen, 2004b) and to the utility maximization theory (Schlich & Axhausen, 2003). However, a critical challenge is to conceptually define clusters of activities – or daily activity centers – from the set of activity locations of each individual (Flamm & Kaufmann, 2006), and to empirically distinguish between the different subclusters of activity locations. Defining such indicators will need assumptions on the minimum number of activity places required for a subcluster and on a distance threshold above which activity places cannot be agglomerated, without losing sight of scale issues.

Spatial behavior by age and sex

Investigating associations between socio-demographic variables and spatial behavior is important to assess the extent to which bias in residential measures of environmental exposures are stratified. These findings show age being strongly associated with spatial behavior. Older participants had a more residential-centered activity space, and overall fewer activity locations, which were more specialized toward food and services than towards recreational and social activities. The decrease in activity space size with increasing age has been reported before (Lord et al., 2009). Other studies have reported that the frequency and distance covered in daily commutes is lower for older adults (Fobker & Grotz, 2006) and that older commuters have shorter trip durations (Newsome et al., 1998). The worsening of health status, the incidence of functional limitations, the resulting lack of autonomy and independence, and the greater social isolation might contribute to such a reduction in the overall mobility of elderly people.

In our study, gender was associated with the size of the activity space and the volume of activities, in line with studies showing that women have smaller commuting distances than men (Madden, 1981; Singell & Lillydahl, 1986) and an activity space more centered on their residential neighborhood (Lord et al., 2009). Such patterns have been attributed to the *household responsibility hypothesis* (i.e., to the unequal repartition of housekeeping and childcare responsibilities) (Turner & Niemeier, 1997). However, other studies did not report any association between gender and characteristics of the activity space (Newsome et al., 1998; Smith & Sylvestre, 2001).

Spatial behavior by socioeconomic status

Our findings suggest that employment status and individual education were strong predictors of spatial behavior. Unemployment and precarious employment status were associated with a higher degree of clustering of the activity locations in the PRN, and with a smaller and more compact activity space. Participants with a precarious job position or unemployed engaged in fewer activities which were more specialized towards food and other services (i.e., they engaged in less recreational activities). This was similar for education, where less educated participants were more likely to restrict their activity locations to their residential neighborhood and less likely to commute longer distances. It is difficult to conclude from the present findings whether low socioeconomic status people are more restricted in their mobility and consequently confined to their residential neighborhood or whether the residential-centering of their activity space is merely a matter of personal preferences (Ross et al., 2000). However, because preferences related to mobility were taken into account in the models, we believe the observed socioeconomic effects are rather attributable to constraints and to a lack of opportunities to travel far from one's neighborhood.

Unexpectedly, participants reporting financial strain had an activity space less centered on their residential neighborhood and engaged in a higher volume of activities, mostly related to food stores and other services. The higher volume of the activities related to food and other services may be related to the fact that such participants are unable pay for recreational activities and that they may be less socially integrated. A potential explanation for the activity space less centered on their residential neighborhood is that participants reporting financial strain may have a lower spatial accessibility to food stores in their residential neighborhood and may travel longer distances to reach cheaper stores.

Spatial behavior by location within the region

As in numerous studies, centrality was a strong predictor of spatial behavior. Living in the suburbs was associated with more activity destinations outside the residential neighborhood. With increasing distance from the city of Paris, individuals had a more extended activity space and reported a lower number of destinations. A comparable *suburbia effect* – more extended activity spaces – was observed in two German cities (Schönfelder & Axhausen, 2002). The urban morphology of suburbs - with lower street connectivity and lower density of stores and destinations - forces suburbanites to travel further distances to reach destinations. Buliung et al. described an urban/suburban behavioral dichotomy in space-time patterns, emphasizing that suburban households have larger and more dispersed activity spaces and travel more kilometers than their urban counterparts (Buliung & Kanaroglou, 2006b).

Additionally, in our study, the activity locations of the suburbanites were less specialized towards food stores and other services. A possible explanation may be the lower availability of and spatial accessibility to a variety of specialized retail stores (i.e. bakery, butcher, fish market, etc.) in the suburbs and the resulting propensity of participants to perform their food shopping in centralized larger supermarkets offering a variety of amenities.

Correlations between patterns of spatial behavior and use of transportation modes

Use of active transportation (walking and cycling) was associated with both having a higher share of one’s activity space in one’s residential neighborhood and engaging in more activities. These finding are coherent with previous literature indicating that non-motorized travels are highly localized around an origin point, i.e., the residence (Frank et al., 2003; Sallis et al., 2004). In contrast, larger scales (i.e., large and elongated activity spaces) require personal or public motorized transportation modes, which is consistent with previous studies reporting a greater car use among suburban dwellers (Dieleman et al., 2002).

Conclusion

These results are important for studies on health and place for three reasons. First, individuals are mobile and mobility patterns differs, which means exposure to environmental conditions needs to account for participants’ daily mobility. Second, identifying mobility patterns sheds light on possible specific needs. For example, some individuals may be trapped in their low resource residential neighborhood or may be constantly traveling across low resource environments. Third and finally, the information on spatial behavior that we were able to derive may causally influence or be associated with certain health behavior, for example transportation physical activity or purchasing of foods.

This work is in line with an increasing number of health studies accounting for mobility behavior. The development of technologies, data collection, and analysis methods including use of origin-destination surveys (Kestens et al., 2010; Lebel et al., 2012; Setton et al., 2011) or GPS tracking (Hurvitz & Moudon, 2012; Kerr et al., 2011; Rainham et al., 2008; Thierry et al., 2013; Zenk et al., 2011) allows researchers to improve the assessment of multiple environmental exposures (Chaix et al., 2013b). These novel data and associated analytic strategies may lead to reconsider the importance of environmental effects on health, with a potential underrepresentation when using residential environment only (Chaix et al., 2013a; Chum, 2013). Overall, more accurate measures of environmental exposures and their effects on health will provide better evidence for public health policies and interventions promoting healthy behaviors including active living.

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Table 1. Spatial and behavioral indicators considered for the typology of spatial behavior

Indicators	Measurement approach	References
Indicators related to the lifestyle		
Number of activity places	Count of activity places	(Buliung et al., 2008; Dijst, 1999b; Lord et al., 2009; Schönfelder & Axhausen, 2002, 2003, 2004a, b)
Number of visits to places per week	Number of activity places per individual multiplied by the frequency of visit per week to each location, excluding the residence	(Buliung et al., 2008; Schönfelder & Axhausen, 2002, 2003, 2004a, b)
Number of activity types	6 types of activities considered: 1-Residential; 2-Work; 3-Food and other services; 4-Transport station/stop; 5-Recreational activity; 6- Social activity	(Buliung et al., 2008; Rai et al., 2007; Schönfelder & Axhausen, 2004b)
Individual quotient of food stores and services	Comparison of the proportion of food and other services for each participant to the proportion of other activities	(Pumain & Saint-Julien, 1997)
Individual quotient of recreational activities	Comparison of the proportion of recreational activities for each participant to the proportion of other activities	(Pumain & Saint-Julien, 1997)
Individual quotient of social activities	Comparison of the proportion of social activities for each participant to the proportion of other activities	(Pumain & Saint-Julien, 1997)
Indicators related to the geometry of the activity space		
Perimeter of the convex hull ***(Figure 1a)***	GIS processing: perimeter of the smallest polygon containing all the activity locations of the participant (unit: km)	
Surface of the convex hull ***(Figure 1a)***	GIS processing: surface of the smallest polygon containing all the activity locations of the participant (unit: km²)	(Buliung et al., 2008; Sherman et al., 2005)
Major to minor axis ratio ***(Figure 1b)***	GIS processing: ratio of the axes of a standard deviational ellipse weighted by the annual frequency of visits to places	(Lord et al., 2009; Newsome et al., 1998; Schönfelder & Axhausen, 2004a)
Gravelius compactness coefficient	GIS processing: activity space represented by a Convex Hull. $K = P / (2\sqrt{\pi A})$ (where P = perimeter and A = surface)	(Bendjoudi & Hubert, 2002; Gravelius, 1914)
Index of eccentricity	GIS Processing: ratio of the distance between the residence and the centroid of the standard deviational ellipse to the length of major axis	(Lord et al., 2009)

Density of activity locations in the standard deviational ellipse	GIS processing: ratio of the number of activity places to the surface of the standard deviational ellipse	
Minimal road network distance from the residence to an activity place ***(Figue 1c)***	GIS processing: minimal distance from the residence to an activity place using the road network	(Arcury et al., 2005)
Maximal road network distance from the residence to an activity place ***(Figue 1c)***	GIS processing: maximal distance from the residence to an activity place using the road network. For activity locations outside Ile-de-France, the distance was approximated with the Euclidian distance.	
Median road network distance from the residence to all activity places	GIS processing: median distance from home to all activity places using the road network	
Indicators related to the importance of the residential neighborhood		
Degree of attachment to the PRN	Scale 0-6; 6=high attachment	
Percentage of visits to places in the residential neighborhood	GIS processing: count of visits to places within the 500 m road network buffer centered on the residence divided by the total number of visits to places	
Number of activity locations in the PRN	Count of activity locations in the PRN	
Percentage of visits in the PRN	GIS processing: count of visits to places in the PRN divided by the total number of visits to places	
Surface of the PRN	GIS processing: unit: km^2	
Proportion of the overall activity/perceived space covered by the PRN[a]	GIS processing: percentage of the activity/perceived space (resulting from the merge of the PRN with the activity space convex hull) covered by the PRN	
Proportion of the activity space covered by the PRN[a] ***(figue 1d)***	GIS processing: percentage of the activity space convex hull covered by the PRN	
Gravelius compactness coefficient for the PRN	GIS processing: Gravelius compactness coefficient calculated for the PRN	(Bendjoudi & Hubert, 2002; Gravelius, 1914)
Index of eccentricity for the PRN	Shortest distance from the residence to the PRN boundary divided by the radius of a circle of the same area than the PRN	

PRN, Perceived residential neighborhood.

[a] Both the numerator and the denominator can differ between these two indicators. The two indicators are exactly similar for the participants for whom the PRN is entirely comprised within the

activity space convex hull. However, they differ when at least part of the PRN is out of the activity space convex hull.

Table 2. Selected characteristics of the RECORD participants included in the present study (n=2062)

Variable	Category	Value
Sex (%)	Female	31
Age (mean, years)	_	51
Citizenship (%)	French	83
Individual education (%)	High	23
	Middle-High	18
	Middle-Low	28
	Low	31
Household income per consumption unit (%)	High (>1750 € per month)	33
	Medium (1125–1750 € per month)	33
	Low (<1125 € per months)	34
Employment status (%)	Stable	50
	Unstable	13
	Unemployed	15
	Other	22
Location in the region (%)	Center	27
	Inner suburbs	46
	Outer suburbs	27

Table 3. Factor analysis of indicators of spatial behavior, VERITAS-RECORD data (n=2062)					
	Centering of the activity space on the residential neighborhood	Size of the activity space	Volume of activities	Specialization of the activity space	Elongation of the activity space
% of variation explained	35%	20%	16%	10%	9%
Surface of the convex hull	-	0.78*	-	-	-
Perimeter of the convex hull	-	0.92*	-	-	-
Gravelius compactness coefficient	-	-	-	-	0.82*
Major to minor axis ratio	-	-	-	-	0.74
Number of activity places	-	-	0.83*	-	-
Number of visits to places per week	-	-	0.80*	-	-
Number of activity types	-	-	0.60	-0.49	-
Index of eccentricity	-	-	-	-0.47	-
Number of activity locations in the PRN	0.50	-	0.71	-	-
Percentage of visits to places in the PRN	0.67	-	-	0.43	-
Proportion of the activity space covered by the PRN	0.88*	-	-	-	-
Proportion of the overall activity/perceived space covered by the PRN	0.88*	-	-	-	-
Percentage of visits to places in the residential neighborhood	0.39	-	-	0.48	-
Maximal road network distance from home to an activity place	-	0.88*	-	-0.40	0.37
Median road network distance from home to activity places	-	0.36	-	-0.49	-
Individual quotient of food stores and services	-	-	-	0.72	-
Individual quotient of recreational activities	-	-	-	-0.36	-
Individual quotient of social activities	-	-	-	-0.37	-

Loading factors higher than 0.75 are flagged with a ‘*’. Values lower than 0.3 are not reported.

Table 4. Associations between individual socio-demographic characteristics and the different components of spatial behavior (n=2062)

	Centering of the activity space on the residential neighborhood	Size of the activity space	Volume of activities	Specialization of the activity space	Elongation of the activity space
	β (95% CI)	**β (95% CI)**	**β (95% CI)**	**β (95% CI)**	**β (95% CI)**
Male (vs. female)	0.01 (-0.07, 0.10)	0.09 (0.00, 0.18)	-0.10 (-0.18, -0.02)	-0.01 (-0.09, 0.07)	0.07 (-0.01, 0.16)
Age (1 year increase)	0.01 (0.00, 0.01)	0.00 (-0.01, 0.00)	-0.01 (-0.01, 0.00)	0.01 (0.00, 0.01)	0.00 (-0.01, 0.00)
French citizenship (vs. other)	-	-	-0.12 (-0.23, -0.02)	-	-
Individual education (vs. high)					
Middle-High	-	-	0.03 (-0.09, 0.15)	0.07 (-0.4, 0.19)	-
Middle-Low	-	-	-0.10 (-0.21, 0.01)	0.11 (0.00, 0.21)	-
Low	-	-	-0.36 (-0.46, -0.25)	0.25 (0.14 0.35)	-
Employment Status (vs. stable)					
Unstable	0.27 (0.14, 0.39)	-0.11 (-0.24, 0.02)	-0.06 (-0.18, 0.06)	0.25 (0.13, 0.37)	-0.25 (-0.37, -0.12)
Unemployed	0.44 (0.32, 0.55)	-0.18 (-0.31, -0.06)	-0.23 (-0.34, -0.12)	0.55 (0.44, 0.66)	-0.26 (-0.38, -0.14)
Other	0.39 (0.26, 0.51)	-0.22 (-0.35, -0.09)	-0.25 (-0.37, -0.13)	0.43 (0.32, 0.55)	-0.21 (-0.34, -0.09)
Income (vs. high)					
Medium	-	-	-	-	-0.13 (-0.23, -0.04)

Low	-	-	-	-	-0.07 (-0.18, 0.03)
Financial strain					
(vs. not)					
Rarely	-0.04 (-0.14, 0.05)	-	0.03 (-0.06, 0.12)	0.04 (-0.05, 0.13)	-
Frequently	-0.11 (-0.21, -0.02)	-	0.10 (0.00, 0.20)	0.11 (0.2, 0.20)	-
Ownership score					
(vs. high)					
Middle	-	-0.13 (-0.25, -0.01)	-		-
Low	-	-0.14 (-0.25, -0.03)	-	-	-
Systematic use of the nearest shop	0.20 (0.11, 0.29)	-0.16 (-0.25, -0.06)	-	0.10 (0.01, 0.19)	0.15 (0.05, 0.24)
Willingness to travel out of the neighborhood to access new types of activity	-0.19 (-0.28, -0.09)	-	-	-	-
Location in the region (vs. center)					
Inner suburbs	-0.49 (-0.62, -0.37)	0.05 (-0.09, 0.20)	-0.51 (-0.61, -0.41)	-0.23 (-0.35, -0.12)	-
Outer suburbs	-0.61 (-0.75, -0.48)	0.48 (0.33, 0.64)	-0.87 (-0.98, -0.76)	-0.30 (-0.43, -0.18)	-
Null model ICC	0.075	0.069	0.120	0.026	0.029
Full model ICC	0.017	0.025	0.004	0.014	0.043
Null model AIC	5593.7	5757.0	5478.4	5417.1	5461.8

Full model AIC	5435.7	5706.3	5277.3	5196.3	5425.6

AIC, Akaike Information Criterion; CI, confidence interval; ICC, intraclass correlation coefficient (proportion of the total variance explained by the variance between the municipality units).

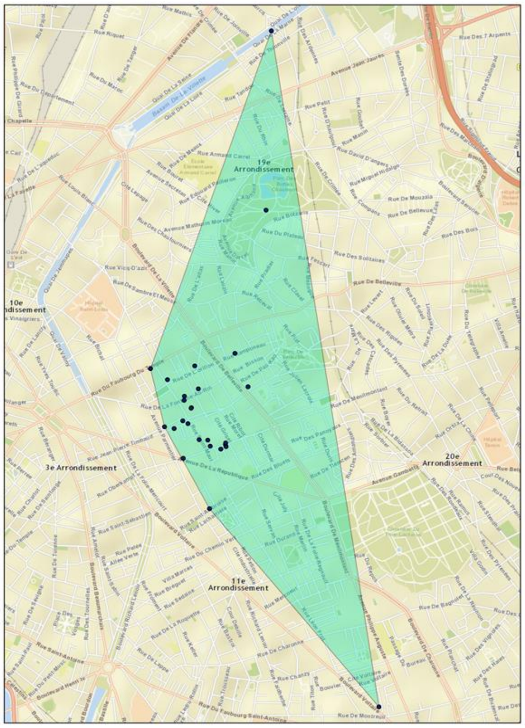
Table 5. Average weekly number of days (standard deviations) of use of transportation modes according to the components of spatial behavior divided in three categories (n=2062)

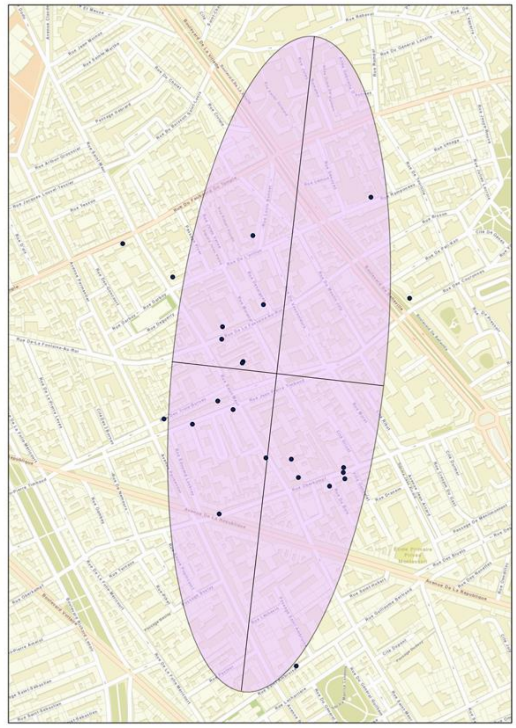
	Walk		Bicycle		Public transport		Car	
	M (SD)	JT test p value	M (SD)	JT test p value	M (SD)	JT test p value	M (SD)	JT test p value
Centering of the activity space on the residential neighborhood								
High	6.0 (2.0)		0.7 (1.7)		2.0 (1.8)		1.1 (1.3)	
Medium	5.4 (2.4)	<.001	0.5 (1.4)	0.001	2.2 (2.0)	0.229	1.6 (1.4)	<.001
Low	5.0 (2.6)		0.4 (1.4)		2.0 (2.1)		1.9 (1.5)	
Size of the activity space								
High	5.2 (2.4)		0.5 (1.4)		2.2 (2.0)		1.8 (1.4)	
Medium	5.7 (2.2)	0.042	0.5 (1.5)	0.636	1.9 (1.9)	0.540	1.5 (1.5)	<.001
Low	5.4 (2.4)		0.6 (1.6)		2.1 (2.0)		1.3 (1.4)	
Volume of activities								
High	6.1 (1.8)		0.7 (1.6)		2.9 (1.9)		1.1 (1.2)	
Medium	5.5 (2.3)	<.001	0.5 (1.6)	<.001	2.1 (2.0)	<.001	1.6 (1.5)	<.001
Low	4.6 (2.7)		0.4 (1.4)		1.2 (1.8)		1.9 (1.5)	
Specialization of the activity space								
High	5.3 (2.4)		0.4 (1.3)		1.7 (1.9)		1.4 (1.4)	

Medium	5.6 (2.3)	0.818	0.6 (1.6)	0.325	2.2 (2.0)	<.001	1.5 (1.4)	0.022
Low	5.4 (2.4)		0.6 (1.6)		2.3 (2.0)		1.6 (1.4)	
Elongation of the activity space								
High	5.4 (2.3)		0.5 (0.5)		2.3 (1.9)		1.4 (1.3)	
Medium	5.4 (2.4)	0.568	0.5 (1.4)	0.118	2.1 (2.0)	<.001	1.5 (1.5)	0.003
Low	5.5 (2.4)		0.7 (1.7)		1.8 (2.0)		1.7 (1.5)	

JT test, Jonckheere-Terpstra test

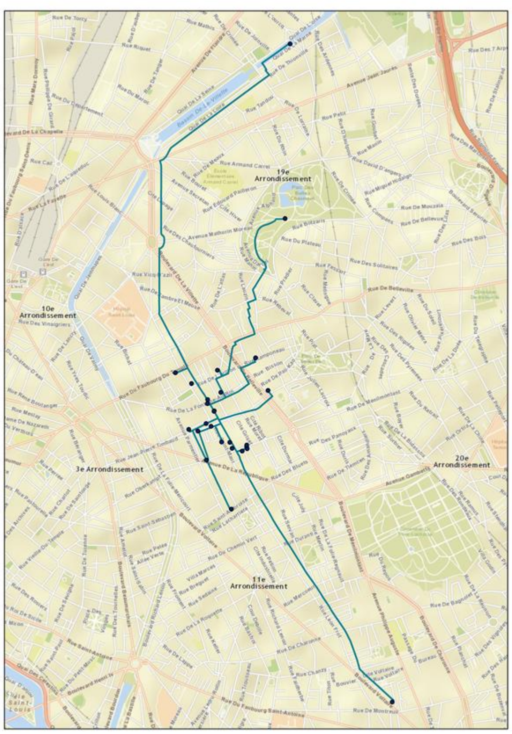
Figure 1. Examples of indicators of spatial behavior

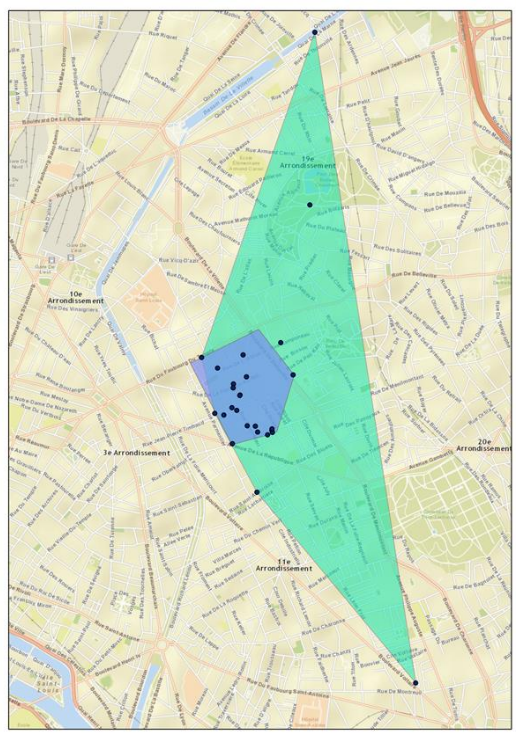




a) Perimeter and surface of the convex hull

b) Major to minor axis ratio of the ellipse





c) Road network distance from home to activity places

	d) Proportion of the activity space covered by the perceived residential neighborhood
Legend	Activity place
Convex hull	Shortest path
Standard deviational ellipse	Perceived residential neighborhood