A GPS-Based Methodology to Analyze Environment-Health Associations at the Trip Level: Case-Crossover Analyses of Built Environments and Walking

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GPS tracking in neighborhood and health studies: a step forward for environmental exposure assessment, a step backward for causal inference?

Keywords:

Global positioning system

Environmental exposure assessment

Neighborhood

Selective daily mobility

Transportation and health

Highlights

- Combining GPS and GIS allows for advances in environmental exposure assessment.

- However, selective daily mobility precludes assessment of causal environmental effects.

- A solution is to integrate the Public health and Transportation approaches to GPS studies.

- Future studies should combine GPS, accelerometers, and electronic mobility surveys.

- Correcting exposure measures and improving study designs may permit mitigating bias.

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Funding

In addition to the funding sources of the overall RECORD Study, the RECORD GPS Study is supported by: CERTU (Center for studies on road networks, transport, urban planning, and public construction) and DGITM (General Directorate of Infrastructures, Transport, and the Sea) of the French Ministry of Ecology; INPES (the National Institute for Prevention and Health Education) and IReSP (the Institute for Public Health Research); ARS of Ile-de-France (the Ile-de-France Region Health Agency); STIF (the Ile-de-France Region Transportation Authority); and RATP (the Paris Public Transport Operator). We are grateful to these institutions that provide support to the RECORD GPS Study and to the members of these institutions for their follow-up of the study (Laurent Jardinier, Tristan Guilloux, Nadine Asconchilo, Colette Watellier, Pierre Arwidson, Mélani Alberto, Christelle Paulo, Sophie Mazoué, and John Séraphin). These partners provided general advice for the RECORD GPS Study but had no role in the writing of and decision to submit the present commentary for publication.

Recent studies have relied on GPS tracking to assess exposure to environmental characteristics over daily life schedules (Almanza et al., 2012; Elgethun et al., 2003; Rodriguez et al., 2012; Wheeler et al., 2010; Zenk et al., 2011). Combining GPS with Geographic Information Systems offers the opportunity to take a step forward in the measurement of environmental exposures (Duncan et al., 2009; Krenn et al., 2011). However, there are concerns associated with the interpretation of the resulting associations with health outcomes, to the extent that these studies may represent a step backward in terms of assessment of causal environmental effects.

GPS tracking for improved assessment of environmental exposures

With the growing recognition that most people only spend a limited amount of time each day in their residential environment, there is a large consensus that one of the most serious limitations of neighborhood and health literature to date is its systematic focus on residential neighborhoods (Chaix, 2009; Chaix et al., 2012c; Cummins, 2007; Matthews, 2011; Rainham et al., 2010). Strategies to incorporate daily mobility in neighborhood and health studies include standard mobility surveys (Kestens et al., 2012) or surveys of regular destinations based on electronic mapping tools (Chaix et al., 2012c). Additionally, GPS tracking appears as a way to move environmental exposure assessment from an exclusively residential to a more comprehensive multiplace perspective that accounts for the multiple daily activity places (Zenk et al., 2011).

Selective daily mobility as a major source of bias in GPS studies

A commentary of selected literature

Our aim was to evaluate the methods and the implicit and explicit rationale and objectives in the literature for correlating environmental information around GPS locations with health behaviors and outcomes. Rather than a systematic review that offers a high level of generalization (Krenn et al., 2011), the analytical strategy selected to achieve our aim was to perform a commentary of published articles, which allows for a detailed examination of studies and of the formulations used to report their objectives, analytical design, and interpretation of findings. The present commentary focuses, not on one article as usual, but on four articles for a more informative analysis, all four articles published in Health & Place (Almanza et al., 2012; Lachowycz et al., 2012; Rodriguez et al., 2012; Zenk et al., 2011). However, the issues discussed in the present article also apply to a number of other GPS studies published in the field of Public health or Nutrition (Duncan and Mummery, 2007; Oliver et al., 2010; Quigg et al., 2010; Wheeler et al., 2010). The four studies were selected for the differences in their objectives (descriptive or inferential) and related interpretation of findings and for the differences in their analytical strategies (GPS point-level analysis or individual-level analysis).

The first reviewed study (Lachowycz et al., 2012) analyzed GPS data collected every 10 seconds and accelerometer data collected for 10 second epochs (periods of data collection) during four school days and at least one weekend day for 614 children aged 11-12 years (Bristol, UK, PEACH cohort, 2007-2009). The authors performed a "momentary" investigation, i.e., analyzed the data at the epoch level (one statistical observation per 10 second epoch) with a random effect at the individual level. More precisely, we refer to this approach as the "contemporaneous momentary design" because information on the location and related context and on the outcome (accelerometry) was collected at the same moment. The objectives of the study were descriptive, i.e., to "record the environments where different intensities of physical activity take place" and to "investigate the actual use of greenspaces". The authors sought to describe behavioral contexts rather than to perform inferences on the effects of contexts on behavior (the "analysis did not consider how use of green space may be affected by how accessible it is to the child”). In accordance with these descriptive objectives and with their “contemporaneous momentary” analytical strategy, the authors did not report the results as associations that attempt to reflect the causal effects of environments on behavior. Instead, as their main findings, the authors descriptively indicated that the majority of moderate-to-vigorous physical activity took place indoors while a substantial proportion of outdoor physical activity was performed in green spaces.

Commenting on the literature, the authors criticized previous studies on the grounds that they measured exposures in residential environments and were “often unable to consider the actual locations where physical activity takes place”. As discussed below, however, assessing where physical activity occurs does not permit causal inference of environmental effects on physical activity. Rather, for such an inferential aim, the challenge is to assess whether physical activity opportunities are accessible from the different geographic contexts visited in daily trajectories.

The second study reviewed here (Rodriguez et al., 2012) analyzed data on 293 adolescent females (15-18 years old) collected for six consecutive days by GPS every 60 seconds and by accelerometers for 60 second epochs (Minneapolis and San Diego, USA). GPS points located within 50 m of the residence or school were discarded, to exclude activities at home or school. The study relied on a contemporaneous momentary design: the analyses were conducted at the epoch level, considering point-by-point information on the intensity of physical activity and on the built environment in 50 m buffers around each GPS point.

Whereas the previous article (Lachowycz et al., 2012) mostly had descriptive aims, the article by Rodriguez switches between two perspectives: identifying causal environmental effects and describing behavioral contexts. The authors suggested that GPS tracking allows researchers to more accurately identify the environmental opportunities and barriers that influence physical activity. However, when interpreting their findings, they focused more descriptively on behavioral contexts, indicating that “understanding the places were physical activity and sedentary behaviors occur appears to be a promising strategy to clarify relationships”. While we agree with this statement, we emphasize below that the sole description of behavioral contexts is not necessarily a step forward towards the appraisal of causal environmental effects on behavior.

The authors reported that, after adjustment, the odds of high physical activity intensity were higher in GPS locations with parks, schools, and high population density, and lower in GPS locations with more roads and food outlets. The descriptive nature of these findings is illustrated, for example, by the argument that the lower odds of intense physical activity near food outlets “may be capturing sedentary behavior, when participants visit malls with outdoor areas, or restaurants with outdoor seating”. These findings simply suggest that people are by essence less physically active in specific places (e.g., restaurants, movie theaters, etc.) than in others (e.g., parks).

The third reviewed study (Almanza et al., 2012) relied on GPS and accelerometer data (30 second intervals/epochs) collected for seven days for 208 children aged 8–14 years from The Preserve smart growth community in California (USA) and six conventional communities situated nearby. Interestingly, the study was designed to rule out selective residential migration biases by comparing families who moved to the smart growth community with families who initially considered moving there but did not. Analytically, the authors compared the contemporaneous momentary analytical design used in the Lachowycz and Rodriguez studies (epoch-level analyses) with a more conventional individual-level analysis.

Contemporaneous momentary analyses revealed a positive relationship between greenness at the GPS point and the likelihood of moderate-to-vigorous physical activity. In individual-level analyses, greenness exposure in the residential neighborhood was defined in two ways: (i) average greenness in the 500 m buffer around the residence; (ii) cumulated time of exposure to greenness at all the GPS points recorded in the residential neighborhood. The association between greenness and physical activity identified in the momentary analysis was retrieved only with the second version of the individual-level greenness exposure variable.

Because of their "spatially-explicit" design (considerable number of locations examined for each participant), contemporaneous momentary analyses were described by the authors as increasing the power to detect associations compared to individual-level analyses. Whether true or not, whereas such simple epoch-level analyses which assess the spatial milieu around individuals at each observation are useful to describe behavioral contexts, they may be inadequate to assess environmental effects on behavior. For example, such simple contemporaneous momentary analyses are unable to demonstrate that an improved spatial accessibility to greenness causally increases physical activity; they simply highlight that green spaces are a more common place for physical activity than many other places such as railway stations or shopping areas.

The individual-level greenness exposure variable defined in 500 m radius buffers around the residence was qualified as "coarser" than the individual-level variable based on the aggregation of greenness exposure at GPS activity locations. Again, in our view, the latter variable is not only more accurate, its meaning is also qualitatively different: whereas the former variable reflects *potential* access to green spaces from the residence, the latter captures the *actual* patterns of use of green spaces in local daily trajectories. As discussed below, such difference has major implications for the interpretation of the associations estimated between the environmental variables and the behavioral or health outcomes.

The standard contemporaneous momentary design was described above as providing descriptive information on behavioral contexts. However, the momentary analysis in Almanza et al. was able to provide richer information because it also examined whether the greenness–physical activity association was of different magnitude for residents living or not in the smart growth community (interaction of effects). Such an interaction in this enhanced momentary analysis allowed the authors to assess whether the overall community design (smart growth or not) influenced the extent to which spending time in greenspaces was associated with increased physical activity levels. The estimated interaction revealed that the greenness–physical activity association was slightly stronger in the smart growth community, even if the confidence intervals were overlapping.

Finally, the fourth reviewed study (Zenk et al., 2011) (Detroit, 2008-2009) analyzed GPS data for 120 adults and older adults (30 second intervals) and accelerometer data for 97 of these participants (one minute epochs). Zenk and colleagues primarily relied on GPS to improve the assessment of environmental exposures, i.e., in the perspective of a contextual expology as denominated in a recent publication of ours (Chaix et al., 2012c). The notion of expology is sometimes used in environmental epidemiology and toxicology to refer to the characterization of individual risks of exposure; in our view, “contextual expology” is a subdiscipline of neighborhood and health research interested in the multiple places and times of exposure to contexts. The objective of Zenk et al. was to overcome the mischaracterization of environmental exposures of studies focused on residential neighborhoods. The authors’ aim was not to assess the *actual* contexts of behavior but the (*potential)* spatial accessibility to services such as fast-food outlets, supermarkets, or parks that may influence health behavior or health. In their analyses conducted at the individual level, exposures were assessed in “daily path areas” derived by buffering all GPS points at 0.5 miles. Interestingly, a comparison of measures of exposures concluded that exposures in the residential neighborhood correlated weakly with exposures in the GPS-based activity space.

Fast-food outlet density measured in the residential neighborhood was associated with none of the three dietary intake outcomes (intake of saturated fat, fruits and vegetables, and whole grains). However, fast-food outlet density in the daily path area (around each GPS point) was positively related to saturated fat intake and negatively associated with whole grain intake. The comment of the authors that “the daily path area may better capture fast-food outlets that were actually utilized” suggests that such an exposure measure reflects the actual behavioral contexts rather than potential access as needed for causal inference on environmental effects.

The study by Zenk is the only reviewed article to discuss this issue of bias, indicating that “activity space fast-food outlet density may be associated with dietary behavior because individuals who want to consume fast-food seek out environments with higher fast-food outlet concentration in order to obtain it” (p. 1158). Arguing that exposure measures that reflect actual behavior generate bias, the authors interestingly suggested that future research should investigate whether the actual use of resources mediates relationships between the potential access to resources around daily activity locations (accessibility) and weight-related behaviors.

Selective daily mobility bias in GPS studies

The description of behavioral contexts (e.g., of the places actually used to exercise) can help plan the provision of health-enhancing services (Duncan and Mummery, 2007; Lachowycz et al., 2012; Quigg et al., 2010). Moreover, this descriptive information is useful to generate hypotheses on environmental resources that support behavior; these causal hypotheses then need to be formally tested through appropriate designs. Our focus here is on such causal inferences on environmental effects (“does the presence of X in the environment influence the behavior of people who live, work, or spend time nearby?”).

In the reviewed studies, exposures to the built and food environments were determined around valid GPS points, including places where individuals specifically go to practice the behavior investigated (e.g., to buy or eat specific foods or to practice physical activity). With such measures, participants with a particular taste for energy-dense food that leads them to eat several days a week in fast-food restaurants would be classified as often “exposed” to a significant density of fast-food restaurants. Similarly, people with advanced knowledge on the benefits of physical activity, positive attitudes toward exercise, and a sufficient self-efficacy to convert intentions into regular physical activity more frequently visit sport or recreational facilities and would therefore appear as more “exposed” to physical activity opportunities. Such intrapersonal factors that encourage specific study participants to regularly use the corresponding environmental opportunities contribute to generate a relationship between environmental factors and health behavior that could be spuriously interpreted as a causal effect of the environment (either in contemporaneous momentary or individual-level analyses). Even GPS studies with refined research questions examining, e.g., which types of greenspaces visited or which characteristics of parks visited are associated with higher physical activity levels do not allow the identification of causal environmental effects because people select the type of parks they go to according to their intended use of these facilities.

In a recent article (Chaix et al., 2012c), in analogy to the well-known “selective residential migration bias” in studies of residential neighborhoods and health (Frank et al., 2007; van Lenthe et al., 2007), we described “selective daily mobility” as a source of confounding of a comparable nature for environment–health studies that account for daily mobility. Such confounding bias is attributable to the causal effect that unmeasured factors (e.g., intrapersonal variables) have on both the places visited during daily life and the health behaviors of interest. The bias stems from the fact that measures of accessibility to given environmental resources are also determined from the locations that were specifically visited to use the corresponding resources, i.e., to practice the behavior of interest. As explained elsewhere, selective daily mobility bias is particularly expected when investigating environmental resources supporting behavior, but is also possible for passive exposure to environmental hazards that influence health (such as air and noise pollution) (Chaix et al., 2012c).

We expect selective daily mobility to be a much more powerful source of bias than selective residential migration. Indeed, even if food, physical activity, and transportation preferences influence neighborhood choice when moving to a new residence, other criteria likely play a significant and perhaps larger role in the choice of the residential neighborhood and dwelling (Kestens et al., 2010b). Obviously, nutritional preferences have a stronger and more overwhelming influence on the daily choice of the physical activity facilities and food outlets visited or not. Accordingly, sorting participants by types of facilities effectively visited in daily life provides much more information on their nutritional preferences than sorting them according to the characteristics of their residential neighborhoods. Hence, a stronger confounding bias is expected from selective daily mobility than from selective residential migration.

Therefore it would be problematic to conclude that an increase in the strength of environment–behavior associations, when switching from a classical residential neighborhood study to a GPS mobility study (both analyzed at the individual level), is attributable to a better assessment of the causal effect of the environment. Even if GPS tracking is a promising strategy to improve environmental exposure assessment, our concern is that the appraisal of causal environmental effects moves one step backward rather than one step forward with such studies, if carelessly implemented.

Strategies to address confounding from selective daily mobility in GPS studies

Correction of measures of exposures and improvement of analytical designs

A first approach, for analyses conducted at the individual level, is to correct measures of multiplace environmental exposures. Theoretically, it is relevant to determine spatial accessibility to resources from so-called anchor points (Chaix et al., 2012c; Flamm and Kaufmann, 2006; Kestens et al., 2010a), i.e., places with important material and symbolic meaning for the individuals, around which they organize their daily activities, and/or where they are relatively constrained to go. At the very least, reference locations from which to compute accessibilities should exclude the places specifically visited to perform activities related to the outcome under study. Accordingly, instead of using GPS data that include all the places visited, it seems important to filter GPS data based on the nature of the activities practiced at the different places, in order to include as much daily activity places as possible for measuring environmental exposures but without biasing the estimated associations. For example, assuming that a participant visits a park for exercise on the way back from his/her workplace to his/her residence, the park would have to be excluded from the set of locations considered to determine greenspace accessibility, to assess whether parks are accessible from the residence and workplace. A more technical issue is whether the trip from the workplace to the residence with its specific itinerary should be included as a set of locations around which to compute greenspace accessibility. A simple answer is that the locations along the itinerary should be taken into account in the assessment of accessibility if the itinerary corresponds to the one that the individual would have followed, had he/she not made a stop at the park. A practical solution for accessibility assessment if the itinerary implies a detour to the park is to replace it by the shortest path between the workplace and the residence.

Another approach that applies to data disaggregated into the multiple activity places visited by each participant may be, as suggested elsewhere (Thierry et al.), to estimate associations between the spatial accessibility to resources from each activity place and the practice of the behavior of interest either within the time frame that follows or within the time frame just before. In comparison with the contemporaneous momentary design discussed above, we refer to this approach as to the lagged momentary design because a time lag is introduced between the measurement of exposure and the measurement of the outcome. In that momentary design, adequate anchor points or reference locations from which to determine spatial accessibility to resources are both the activity place just before the practice of the behavior of interest and the activity place that follows it (Thierry et al.). For example, if a person makes a stop at a fast-food restaurant (as the outcome of interest) just before arriving to his/her workplace, what matters is the spatial accessibility to fast-food outlets from the workplace. However, in specific cases, either or both the activity place just before and the one just after the behavioral outcome may be inadequate anchors or reference locations from which to determine accessibility, for example if the participant makes a stop at a bookstore just nearby his/her sport facility after exercising there in a study of physical activity. In the latter example, the high degree of spatial accessibility to sport facilities from the bookstore spuriously reflects that the bookstore itself was reached from the visited sport facility. As a general rule, valid reference locations around which to compute accessibility include all the activity places that would have been visited by the participant independently of whether the behavior of interest was practiced or not around them.

Overall, assessing the nature of activities practiced at the different places is a necessary complement to GPS tracking to mitigate selective daily mobility biases by selecting/excluding activity places from which to determine accessibilities/exposures.

Data requirement: integrating the Public health / Nutrition and the Transportation approaches to GPS studies

As summarized in Table 1, current studies in the fields of Public health and Nutrition, including the 4 articles reviewed here, do not attempt to decompose GPS tracks into distinct activity places and trips between them. These studies, with few exceptions still at an experimental stage (Oliver et al., 2010; Southward et al., 2012), also do not systematically assess the nature of activities practiced at the different places and the transportation modes for each trip. Differently, in the Transportation field (see Table 1), studies combine GPS tracking with precise mobility surveys that collect information on activities and transportation modes, though often only over one day (Auld et al., 2009; Bohte and Matt, 2009; Flamm and Kaufmann, 2006; Stopher and Collins, 2005). However, Transportation researchers usually do not incorporate accelerometers as Public health / Nutrition researchers do, and therefore lack information on physical activity and energy expenditure, which is also important to detect transportation modes. Clearly, a key challenge for future research is to incorporate the strengths of the two strategies in an integrated approach that combines GPS, accelerometers, and mobility surveys.

To gather data on activities and transportation modes, first one has to identify the activity places in the continuous stream of GPS data and to segment trips between them into a succession of trip stages (a trip stage is a part of a trip based on a single transportation mode); then one has to assess the nature of activities practiced at the different places and confirm the transportation modes between them. The present commentary does not describe in detail the hardware and software infrastructure employed in the RECORD GPS Study to address these two challenges, but provides sufficient information to allow one to understand the difference between the various strategies.

Regarding the first issue, automated algorithms make it possible to detect activity places (e.g., from the stationarity of the GPS trajectory at a given place) and to segment trips between these activity locations according to the transportation modes that were used (Marchal et al., 2011; Thierry et al., 2011; Tsui and Shalaby, 2006). Related challenges pertain to the parameterization of the algorithms (i.e., decisions on the minimum time at a fixed place for activity place detection, on cutoff values for speed and acceleration related to each transportation mode, etc.).

Regarding the second issue, whereas automated algorithms are useful to impute transportation modes (Bohte and Matt, 2009), they are limited in their capacity to impute the exact nature of activities, e.g., based on data from Geographic Information Systems on points of interest and facilities. In the RECORD Study (Chaix et al., 2012a; Chaix et al., 2010; Chaix et al., 2011; Chaix et al., 2012b), an interactive web mapping application (VERITAS) is used to geocode the regular activity places of participants (Chaix et al., 2012c) prior to the GPS assessment. These data can improve the performance of activity recognition algorithms. Still, such algorithms are unable to identify the exact activities practiced in many places (Bohte and Matt, 2009). Investigators are therefore constrained to survey participants during or just after the GPS collection to validate, correct, or complement information on activities and transportation modes.

One option to collect information to further characterize GPS tracks is to rely on web mapping applications denominated prompted recall survey tools because they are based on the electronic presentation of GPS tracks to facilitate or prompt the recall of the places visited (Auld et al., 2009; Bohte and Matt, 2009; Stopher and Collins, 2005). Important features of such survey software are that: (i) they have to be compatible with algorithms that identify activity places and impute information on the nature of activities and transportation modes to minimize the burden for the participants; (ii) they have to allow the participants to confirm or modify the imputed information and to provide answers to additional questions on activity places and trips; and (iii) they should offer both a simplified application usable by the participants themselves and an expert mode with extended functionalities for survey technicians.

Collecting survey data on activities and trips would be useful to Public health researchers, not only to correct the estimated environmental effects on health behavior from selective daily mobility biases. It would also allow them to reconstruct missing portions of trajectories. In the absence of GPS data (loss of signal, empty battery, etc.), surrogate locational information from the survey could be matched to accelerometry data. With this approach, it might be possible to include in the analyses indoor activity places that are often excluded from momentary analyses and to not exclude participants with insufficient GPS data. As a consequence, coupling GPS tracking with a precise mobility survey may help reduce selection biases.

Moreover, information on transportation modes for each trip from a mobility survey combined with GPS and accelerometer data would allow researchers to investigate the relationships between transportation behavior, physical activity, and health as an emerging field of research. For example, in the RECORD Study, GPS and mobility survey data are used to elaborate for each participant an accurate timetable over seven days as the succession of the activity places visited and of the transportation modes between them. Our aim is to analyze the accelerometer data according to this timetable, for example to assess differences in energy expenditure between trips with different transportation modes or chains of modes.

Conclusion

Improving measures of exposure to environmental conditions by accounting for daily mobility patterns is critical. In no way, however, should such improvement be obtained at the expense of the quality of causal inference. An integrated approach combining GPS tracking, accelerometers, and an electronic web-based mobility survey was described as a potentially relevant strategy to neutralize selective daily mobility processes that otherwise bias the estimated effects of multiplace environmental exposures on health and health behavior.

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Table 1

Two approaches for incorporating GPS tracking in studies, and their implications for investigating environmental determinants of active living and health

The classical Public health or Nutrition approach to GPS studies	The Transportation approach to GPS studies
How does it proceed?	
- Does not systematically identify activity places in the GPS stream of data	- Relies on automated algorithms to identify activity places
- Does not survey the nature of activities practiced at the different places (often only the location of the residence and workplace/school is known)	- Surveys the nature of activities (with start and end times) practiced over the follow-up period (or a part of it)
- Usually does not assess the transportation modes used for each trip	- Surveys the transportation modes used for each trip over the follow-up period (or a part of it)
- Determines the number of steps walked, the intensity of physical activity, and energy expenditure based on accelerometry	- Usually does not rely on accelerometry
What are the consequences for the study of environmental determinants of active living and health?	
- Determines environmental exposures based on all GPS locations, irrespective of activities	- Would enable filtering activity places and related trips based on the nature of activities
- Estimates associations that are vulnerable to selective daily mobility biases	- Offers the opportunity to mitigate selective daily mobility biases
- Investigates the correlates of the number of steps walked, activity intensity, and energy expenditure (accelerometry) but lacks precise information on the time spent in the different transportation modes	- Investigates the correlates of time spent in the different transportation modes but would need accelerometry to establish a connection with physical activity and energy expenditure