An Interactive Mapping Tool to Assess Individual Mobility Patterns in Neighborhood Studies

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Using aAn Interactive Mapping Application (VERITAS) to Assess Individual Mobility Patterns in Neighborhood and Health Studies

Opportunities and Challenges for Environmental Exposure Assessment

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Abstract

As their most critical limitation, neighborhood and health studies published to date almost systematically ignored non-residential activity places where individuals travel in their daily lives. Nonetheless, identifying low mobility populations trapped in low-resource environments, assessing environmental exposures cumulated over multiple activity places, and identifying the right activity places for targeting each intervention are important needs for health promotion.

Given the lack of tools to collect locational information on activity spaces, the first aim of the article is to describe VERITAS (Visualization and Evaluation of Route Itineraries, Travel destinations, and Activity Spaces) as an interactive web mapping application allowing researchers to geolocate individuals' activity places, routes between locations, and relevant areas such as experienced or perceived neighborhoods. The second aim is to formalize the theoretical grounds of a contextual expology as a subdiscipline aimed at a better assessment of the spatio-temporal configuration of environmental exposures. Based on activity place data, various indicators of individual spatial behavior (patterns of movement in space) are described, as a key dimension in neighborhood and health research. Preliminary guidance is provided on the successive steps for elaborating variables of multi-place environmental exposure (collection of raw locational information, selection/exclusion of locational data, derivation of an exposure area for measurement, and calculation). "Travel and activity place network areas" are discussed as a relevant construct for environmental exposure assessment. Finally, it is warned that measures of multi-place environmental exposure that improve the stratification of individuals according to true exposures may at the same time increase the magnitude of confounding (selective daily mobility bias processes), if not carefully handled.

Introduction

Neighborhood and health studies have focused on the environmental correlates of diseases.[1-3] However, despite refinements to assess residential environments (e.g., in circular or street network areas centered on the residence; with geographical databases, audits, or survey of residents; etc.),[4,5] studies systematically ignored, with few exceptions,[6-9] individuals' non-residential activity places,[1,4,10-15] resulting in a mischaracterization of environmental exposures.[16] A recent review[1] of studies on cardiometabolic outcomes indicated that as much as 90% of the 131 reviewed studies only accounted for the residential environment, 6% only took into account non-residential exposures (e.g., workplace or school), and only 4% accounted for both the residence and another anchor point. There is little doubt that this reductionism to residential environments, or ignorance of intrinsic "spatial polygamy" (or intimate connection with multiple geographic places[15,17]), is one of the main limitations of neighborhood and health studies.[13,18]

Accounting for daily mobility patterns and activity spaces is important for health promotion, to identify low-mobility populations trapped in low-resource/high-exposure residential environments and mobile populations exclusively travelling across low-resource environments; to correctly assess environmental exposures experienced over multiple activity places; and to identify the adequate activity places (e.g., residence or workplace) for targeting particular interventions.

To contribute to the advent of a new generation of neighborhood and health studies accounting for mobility patterns, the present article first describes the VERITAS application (Visualization and Evaluation of Route Itineraries, Travel destinations, and Activity Spaces) as a tool to geolocate individuals' activity places, routes between locations, and area delimitations of interest. Second, it attempts to formalize the theoretical grounds of a contextual expology (definition in Table 1), discussing methodological challenges related to the assessment of spatial behavior and multi-place environmental exposures.

VERITAS: an interactive geolocating survey tool

The VERITAS application relies on a questionnaire form builder that allows one to develop custom strategies of collection of spatial information. For ease of presentation, VERITAS is described through the VERITAS-RECORD questionnaire designed for the RECORD Study (RECORD[19-25] is interested in the relationships between geographic life environments, individual mobility, and risk factors of cardiovascular diseases). VERITAS-RECORD, for which scientific rationale is provided, is illustrated in Figure 1 and in a video available as Online-Only Material, http://www.youtube.com/watch?v=eWqlyX44_T0&hd=1.

Comment [BC1]: Needs to be replaced by a link to the AJPM website.

VERITAS is a web-based computer tool integrating Google Maps interactive mapping functionalities that allow one to search for, visualize, and geocode participants' activity locations, and geolocate routes between locations and areal delimitations such as perceived/experienced neighborhoods. A computer-assisted questionnaire guides participants through a spatio-temporal cognitive journey (succession of screens with questions and interactive maps) intended to facilitate the restitution reporting of spatial information (point data, polylines, polygons) and minimize memory biases. As the two components of the application, survey questions serve as prompts to stimulate recall, while electronic maps generate more positionnally accurate information than if a simple questionnaire was used.

In VERITAS-RECORD, participants are successively asked to geolocate the list of activity places reported in Figure 1 legend (35997 activity places have been geocoded for the 2500 first participants of the RECORD Study). For most activity types, participants are invited to report destinations they visit at least once a week. It was decided not to specify any particular recall period such as “over the past 6 months”. As exceptions to this once-a-week minimum frequency rule, participants are asked to geolocate workplaces where they spend at least one third of their working time, supermarkets they visit at least once a month, and, without any minimum frequency, their bank, post office, and hairdresser (it was found relevant to construct activity spaces from activity places with different minimum visit frequencies). The VERITAS-RECORD data do not allow one to distinguish participants who do not practice an activity regularly from those who practice it regularly but in different locations. This is an accepted consequence of the fact that VERITAS-RECORD is focused, not on the activities themselves, but on regular visits to given locations. For each activity category, several activity places can be reported.

The interactive geolocating tool is based on the Google Maps Application Programming Interface, allowing users to search addresses and identify services around a location (with a parameterizable search radius). It is possible to save activity place markers retrieved by searches or to create markers by double-clicking on the map. A Google Street view screen is embedded in the application to eventually help participants locating their activity places.

In VERITAS-RECORD, the polygon drawing functionality enables participants to draw the perceived boundaries of their residential neighborhood (Figure 1). A video tutorial showing how to draw the polygon is presented to the participants before the assessment (explanatory multimedia material can be embedded in the application). Once drawn, the polygon shape can be remodeled by moving the polygon vertices on the screen. The participants are asked first to draw their perceived neighborhood boundaries, and second to geocode their regular destinations: ensuring that representation of the latter on the map does not influence assessment of the former will allow one to investigate whether and which regular destinations shape perceived neighborhood delimitations. There are also arguments to conduct the assessment the other way round (first geocode local activity places to improve accuracy in the assessment of perceived neighborhood boundaries).

For each geolocated spatial object, whether a point (location), a polyline (e.g., a trip), or a polygon (e.g., one's perceived neighborhood), it is possible to invite users to provide attribute data pertaining to the object through a small window connected to the object. In VERITAS-RECORD, participants are invited to report (i) the frequency of visit to each destination; (ii) the extent to which they feel attachment to their residential neighborhood and geographic work environment; and (iii) additional information on particular types of activity places, i.e., indoor or outdoor workplace, the transportation mode used at the reported transportation nodes, the type of sport or entertainment activities practiced, etc.

In RECORD, the VERITAS questionnaire is administered by two trained survey technicians constantly supervised by a field coordinator, herself supervised by the principal investigator. Participants are sitting nearby the technician to see the computer screen and can show locations on the map to facilitate geocoding. Data are entered by the technicians but the participants are able, only if they wish so, to take the computer mouse to draw their perceived neighborhood boundaries. The technicians are instructed to take the time needed with participants less familiar with electronic mapping applications (e.g., older people, low socioeconomic status participants) to correctly geolocate their regular destinations. Median time to administer VERITAS among the first 2500 participants was 19 mn (interdecile range: 12 – 38 mn). Self-administered questionnaires are possible with VERITAS, but have not been tested yet.

The VERITAS-RECORD data are downloaded daily from the SQL database on a remote server and checked with a semi-automatic database management program (verification of the addresses, of the number of activity places geocoded per participant, of supermarket names, of other attribute data for activity places, of whether the residence is within the self-drawn residential neighborhood, etc.). The resulting report is discussed every day with the technicians.

The authors are developing a parameterizable web-based version of the software that allows users to collect declarative locational data with other spatial or temporal formats than in RECORD (e.g., routes, sequences of activity places over a short period, etc.).

Accounting for daily mobility in contextual expology: opportunities and challenges

As distinct from life-course residential mobility[26] (that could also be surveyed through VERITAS), daily mobility is defined as the everyday movement of individuals over space between activity places. Daily mobility is of interest in environment–health research,[11] first as a potential source of transportation-related physical activity,[27,28] and second as a vector of exposure to geographic environments.[12,16,29-32] Figure 2 shows that these two reasons for investigating mobility are inferable from a diagram depicting the "environment, mobility, and health" triad.

Strengths and limitations of surveys of regular destinations and GPS tracking

How do surveys of regular destinations[19] (e.g., VERITAS-RECORD) compare with GPS tracking[16,33-38] as strategies among others (e.g., travel surveys or diaries)[11,39] to collect locational information beyond the residence? Based on participants' recall, surveys of destinations provide declarative data, while passive tracking yields objective data. Additionally, the resulting data differ both in their spatial and temporal dimensions (as intimately intertwined). Regarding the spatial dimension, GPS technologies provide nearly continuous polylines, while classical surveys of regular destinations only collect punctual point data for locations (even if regular routes could also be surveyed).[40] Regarding the temporal dimension, surveys of regular destinations are able to assess usual travel destinations of significance over a long period while GPS tracking identifies (almost) exhaustively destinations over more restricted periods (i.e., chronic vs. acute environmental exposures). Moreover, GPS data indicate the temporal sequence of places visited (space-time path[11]), while regular activity place surveys provide non sequential data on temporally disconnected activity places.

In RECORD, it was decided to assess both regular destinations meaningful over a long period with VERITAS to investigate environmental determinants of chronic conditions, and mobility over 1 week through GPS tracking to explore environmental determinants of behaviors such as physical activity. Short-term tracking data may poorly represent locations regularly visited over a long time. Therefore, surveys of regular destinations and GPS tracking provide complementary information for an improved contextual expology.

Biases from integrating regular mobility in contextual exposure evaluation

Accounting for mobility in contextual exposure assessment is a considerable opportunity, but there are pitfalls researchers need to be aware of.

With multi-place exposure variables, the aim is to improve stratification according to true environmental exposures. However, such measures, if not carefully constructed, may simultaneously increase stratification according to other constructs influencing health. Accordingly, accounting for multi-place exposure may, while improving exposure stratification as desired, at the same time increase residual confounding. The potential for *selective residential migration* to confound residential neighborhood effects is widely recognized.[41-43] Similarly, *selective daily mobility* (see Table 1), through which possibly unmeasured factors influence both daily destinations and health, is an additional source of confounding distorting associations between multi-place environmental exposures and health.

Assessment of environmental determinants of health behavior is particularly prone to bias[16] if the locations to which people specifically travel to practice the behavior are incorporated in the measures of multi-place exposure to environmental characteristics that one correlates with the behavior. For example, including the parks where people travel to practice outdoor exercise when determining spatial access to such facilities would likely result in a biased estimate of the corresponding effect. Indeed, in such cases where frequenting immediate contexts of the behavior is often a marker of the willingness to practice the behavior (e.g., frequenting fast-food restaurants as an indication of a personal taste for high-fat foods), measures of multi-place exposure that directly take into account such behavioral contexts could spuriously stratify individuals according to their willingness to practice the behavior.

While confounding is particularly expected for environmental resources supporting behavior, it is also possible when direct health effects of environmental hazards (e.g., air pollution, low socioeconomic status, social violence) are examined. For example, being exposed to a given hazard in multiple environments does not provide information only on exposures but also on, e.g., preference/aversion or absence thereof for particular facets of neighborhoods and related life values, which are themselves potential health determinants. Overall, non-residential environmental effects are particularly prone to bias, because the non-residential environments visited are to a larger extent than residential neighborhoods a matter of flexible choice.

Any increase in the strength of associations when taking into account multi-place rather than exclusively residential exposures may be attributable, not only to improved stratification of exposure, but also to confounding from selective daily mobility.

Deriving indicators of spatial behavior and multi-place environmental exposure

Characterizing spatial behavior

It is of general interest in neighborhood and health studies to characterize individuals' spatial behavior (frequency and spatial patterns of mobility).[8]

The extent to which individuals' daily trajectories are circumscribed by residential neighborhoods likely modifies residential neighborhood influences, with weaker effects expected for mobile populations,[44] possibly explaining why specific groups (the elderly, disadvantaged persons, etc.) are more sensitive to residential neighborhood exposures. In a more elaborated contextual expology, spatial behavior is a key determinant of exposure: individual sociodemographic and psychological profiles and specific environmental characteristics (e.g., access to public transportation) influence individual spatial behavior,[45] which in turn determines environmental exposures.

The VERITAS-RECORD survey of regular destinations and assessment of perceived neighborhood boundaries allow us to characterize spatial behavior as a multi-dimensional construct: as detailed in Table 2, based on VERITAS-RECORD, one can distinguish quantitative indicators of spatial behavior that relate to the overall extension and shape of individuals' activity space[8,45-48] (individuals' spatial range[17] or spatial scope[47]), to the internal structuration of the activity space, and to the status and significance of the residential neighborhood in the overall activity space. It is also likely relevant to summarize these indicators through typologies of spatial behavior.

Such measures are useful to identify low-mobility populations and spatial exclusion or captivity.[45] It is acknowledged that these crude indicators of spatial behavior (rather than spatio-temporal behavior[47] that was only partially assessed in VERITAS-RECORD) do not capture complex spatial and temporal interdependencies between activity places[17] (multistop trip chains,[49] etc.). Also, of relevant note, activity spaces reflect actual spatial behavior, as distinct, first from potential activity spaces (all places where an individual could have been given her/his space-time constraints) and second from mental maps (perceptual action space[50]) which, as personal cognitive constructs, include both locations to which people go and other destinations where they do not go or never have been but of which they have mental representation.[45,51]

Deriving indicators of environmental exposure: moving towards a contextual expology

Recent work promotes improved measurement of neighborhood characteristics with random-effect modeling of survey/audit data[52] or geographic information systems (a field to which we refer as to ecometrics).[53] While ecometrics is interested in the *content of exposures*,[4] there is a need to develop a contextual expology (definition in Table 1), as another subdiscipline interested in the *spatio-temporal configuration of exposures*, allowing researchers to define multi-place or activity space-bounded measures of exposure.[32]

As detailed in Table 3, a contextual expology involves four steps: (i) *collection* of raw locational information for participants (where and when); (ii) *selection* of raw locational information to retain for exposure measurement; (iii) *transformation* of raw locational information collected as point data (activity places), polylines (travel paths), or polygons (perceived neighborhood geolocated, area-level geocoding) in a spatial basis or spatial ground of for the measurement of environmental exposures (most often areas but possibly polylines or points as the basis to extract environmental information); and (iv) linkage of environmental information for *calculation* of exposure measures. As data collection (step 1) was discussed above, Based on discussions of step 1 in the previous sections, the remaining of the manuscript focuses on the selection (step 2) and transformation (step 3) of locational information for measuring environmental exposuresnext paragraphs focus on steps 2 and 3 of the measurement process.

Which locational information to retain/discard for exposure assessment?

A relevant distinction when selecting locational information for exposure assessment is whether the focus is on direct effects of environmental hazards on health or on the influence of accessibility to environmental resources on health behavior. Contrary to the former case, when assessing accessibility to environmental resources influencing behavior, it is critical to exclude from the set of locations considered for measurement places where people intentionally go to practice the behavior or its opposite (e.g., exclude destinations visited to perform outdoor recreational activities when computing accessibility to green/open spaces). To solve that recently described bias,[16] it is critical, with a regular destination survey or GPS tracking, to collect information on activities practiced at the different places visited for a selection of locations to retain for assessment of spatial access to behavioral opportunities.

A safer but restrictive strategy to compute accessibility to resources is to determine it only from spatial anchor points[12,54] (defined in Table 1). Such anchor points primarily include the residence and workplace, but also minor daily life centers such as one's children's school or parents' residence around which it is meaningful to compute accessibilities.[55] However, restricting measurement areas to a limited number of anchor points may lead to excessive discard of locational information.

Finally, selection of activity places to retain for measurement is necessary but insufficient, as choices of daily life centers such as the residence or workplace are themselves determined by preferences also influencing the outcomes of interest. Therefore, a complementary strategy is to develop questionnaires that capture personal criteria for choosing daily life environments and cognitive variables related to health behavior (e.g., attitudes/beliefs related to the behavior, willingness and motivation to engage into it) that influence the environments visited, for improved adjustment of regression models.[4,43,56]

Which transformation to define the spatial basis of measurement?

Overall convex activity space polygons (ellipses or convex envelopes derived from all activity places collected in VERITAS-RECORD) are likely not appropriate for assessing exposures. As exemplified in Figure 3, even after elimination of outliers,[47] an overall convex activity space polygon based on all travel destinations and routes often does not reflect the extent of territories with which the person is familiar:[45] such an area may indeed encompass unfrequented portions of territory (bold dashed lines on Figure 3, see legend).[32]

As illustrated in Figure 3, rather than using overly broad convex areas (*joint transformation* of all activity places in an overall polygon), it is likely more relevant to derive measurement areas by buffering all or part of the travel and activity place network geometry[13,54] (defined in Table 1). Such *feature-by-feature transformation* of the components of the network provides a "travel and activity place network area" that more closely reflects hazards or resources along daily trajectories. As described in Table 3, other transformations to derive measurement areas include kernel density estimation or cluster detection techniques.[45,63]

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Buffering provides different types of measurement areas depending on the raw locational information collected (see Table 3). When only regular destinations are surveyed but not the routes between them (as in VERITAS-RECORD), an approximate[57] strategy is to generate road-network travel paths between daily life centers (e.g., between the residence and workplace) and between daily life centers and nearby functionally affiliated activity places.[45] Buffering of these imputed travel routes (shortest path network areas) may improve measurement of environmental exposures.[8,39,58]

One step further in terms of data requirement, Kwan's space-time measures of potential access[39,58] further account for the chronological order of activities in the daily program, for time-budget constraints between each activity place and the next one (in fact the time effectively used rather than the time that was truly available[57]), and for the speed of travel between locations. However, such measures inspired from time geography[59] in which spatial access depends on time budget are generally grounded on short-term travel diaries (e.g., 2 days), and would be difficult to construct when regular destinations are of interest to assess chronic exposures relevant over a longer period.

Buffering of raw locational information implies specifying the type of buffering and radius size (see Table 3). Among criteria to consider to determine radius size, an important issue is whether a measure of potential contact or effective contact to the environment is of interest (distinction between potential and experienced activity spaces[12,13]). Measures of potential contact are derived by buffering the observed spatial footprint with a certain radius, whereas measures of effective contact are obtained by restricting the radius size to the null (and extracting exposure values at the exact locations of activity places and travel paths) or close to the null. Measures of potential contact are of interest, for both environmental resources and exposures, when no information is available on the individuals' usual patterns of movement around the geocoded locations, as a way to approximate the exposure area of participants. On the opposite, when the spatial footprint over a period is exactly known, measures of potential contact are useless for evaluating exposures to environmental hazards (measures of effective contact are more informative), but measures of potential contact remain of interest to evaluate accessibility to environmental resources (e.g., services). Strategies to determine buffering radius size include a mixture of hypothesis-based reasoning and exploratory sensitivity analyses comparing radius sizes.

Conclusion

The VERITAS application and related theoretical considerations aim to contribute to the advent of a next generation of studies, with refined research questions, novel data, and renewed analytical strategies. These developments foster a shift of paradigm from the "neighborhood and health" classical dyad to a "neighborhoods, mobility, and health" triad.

These more realistic empirical models of contextual/ecological determinants of health that integrate rich information on individual spatial behavior will provide more informative support for public health decision making. An important matter for service provision is to identify low-mobility or spatially isolated populations who lack spatial access to resources. Moreover, accurate assessment of (multi-place) environmental exposures and their health effects will help prioritizing public health interventions.

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Figure Legends

Figure 1. Screen copy of the VERITAS-RECORD application.[a]

[a]The application allows one to geolocate participants' network of regular destinations and assess the perceived boundaries of their residential neighborhood (the green polygon on the map). The following activity places were geocoded in RECORD (not only places of activities related to health but any regular destination as relevant to environmental exposure assessment): place of residence, secondary or alternative residences, places of work, supermarkets, outdoor markets, bakeries, butcher shops, fruit and vegetable shops, fish stores, cheese merchants, other specialized food stores, tobacco shops, banks, post offices, hairdressers, transportation stations used from the residence, sport facilities, entertainment facilities, places for cultural activities, places for community or spiritual activities, places where participants take relatives, and places where they visit people (healthcare destinations were assessed from another source).

Figure 2. Theoretical illustration of the environment, mobility, and health triad.[a]

[a]The environment influences mobility (relation 1) and health (relation 4). Mobility, through the degree of engagement in active transport, influences health (relation 2). Mobility is a vector of exposure to multiple environments (relation 3). Health status may constrain to live and travel in specific environments (relation 5), and influences mobility through possible handicap (relation 6). The two mediated relationships with health as the final outcome are of particular interest to us: (i) the environment may influence health through mobility habits (wide dotted lines, relations 1 and 2), encouraging us to investigate active transport as a mediator; (ii) mobility influences health in shaping the environments to which individuals are exposed (double lines, relations 3

and 4), encouraging us to develop a contextual expology. It is hypothesized that preferences related to activity places, mobility modes, and health behavior are correlated, thereby creating potential confounding (narrow dotted lines).

Figure 3. Illustration of the difference between overall convex activity spaces and travel and activity place network areas in the measurement of environmental exposures (fictive example).[a]

[a]Part A represents the raw locational information collected: main daily life centers (R for residence and W for workplace), minor daily life centers (P for one's parents' residence and S for a regularly visited sport club), other activity places, and travel paths to the main activity places (e.g., collected from VERITAS). Part B represents an overall convex activity space defined as the convex envelope of all activity places and routes. The bold dashed lines in the middle refer to territories with which the participant is not familiar at all, considering that high speed train is used to travel from residence to work. In Part C, an exposure area based on the notion of travel and activity place network is derived by buffering the activity places and walking and car-driving travel paths but not those by high-speed train or underground train (from residence to work and from work to the sport club, respectively).

Table 1. Short glossary of technical terms or expressions used in the article

Activity space	Set of spatial locations visited by an individual over a given period, corresponding to her/his exhaustive spatial footprint; the regular activity space is the subset of locations regularly visited over that period
Contextual expology	Subdiscipline interested in the spatio-temporal configuration of exposure (spatial and temporal patterns of mobility) for improving measurement of environmental exposures (not the “what” but the “where” and “when” of exposure[14]); it relates to the collection and transformation of locational information to define a spatial ground of measurement and to the extraction and aggregation of environmental information on this basis to derive environmental exposure variables
Daily mobility	Everyday movement of individuals over space between activity locations
Multi-place environmental exposure	Exposure to a given environmental characteristic across the multiple locations visited
Raw locational information	Any information on the spatial location of individuals at any point of time in their life in the format in which it was collected (e.g., in traditional studies, the identification code of the current residential administrative unit was the only raw locational information available)
Selective daily mobility	Selective daily mobility refers to the fact that people who visit particular activity places during their daily lives have particular characteristics (sociodemographic, psychological, or cognitive characteristics; behavioral habits; etc.) that also influence their health status
Spatial anchor points	Spatial anchors or pivots[14] (also denominated reference locations,[39] fixed activity places,[60] bases, or core stops[50]) refer to daily life centers[12,54] (i) to which individuals spend a significant share of their time, (ii) which have important material and symbolic meanings, (iii) around which individuals organize their daily activities, and (iv) to which people are relatively constrained to go (the spatial fixity and temporal rigidity[50] of these quasi-obligatory activities imply that they cannot be easily relocated or rescheduled[59,60])
Spatial basis / ground of measurement	Most commonly one or several polygon(s) but possibly polyline(s) or point(s) derived through a transformation of raw locational information and used to extract environmental data to calculate the exposure variable of interest
Spatial behavior	Frequency and spatial patterns of mobility (multi-dimensional construct described in Table 2)
Travel and activity place	As a geographical system,[54] such network comprises (i) local activity

network area	spaces centered on major or minor daily life centers (that are also travel hubs) and (ii) more optional destinations isolated or not from these activity spaces, all of which related to each other by (iii) transportation corridors (not collected in VERITAS-RECORD) allowing no exchange, little exchange, or significant exchange with the surrounding environment depending on transportation modes, time constraints, preferences, etc.[39,58]

Table 2. Summary of options (among others) to characterize spatial behavior[a]

I – Geometric representation of the activity space through overall convex polygons as ecological containers[46] (and related quantitative parameters)

- A – Application
  - 1 – Overall activity space (all types of destinations)
  - 2 – Domain-specific activity space, e.g., the food purchasing space, the healthcare seeking space
- B – Tools
  - 1 – Standard deviational ellipse[61] or confidence ellipse[45] (centrographic measure, point pattern analysis): reflects, with its optimally oriented major and minor axes, the location, coverage, dispersion (ratio of major to minor axes), and orientation of a set of points[46,47,61] (weighted or not by visit frequencies)
  - 2 – Home–work ellipse[57]: with the major axis of the ellipse going from the residence to the workplace as the two foci of the ellipse, with the minor axis determined by the furthest other activity place
  - 3 – Convex envelope[47]: smallest convex polygon containing a set of points

II – Internal structuration of the activity space

- A – Number of regular destinations and related visit frequencies
- B – Activity space structured around a unique or multiple daily life centers
- C – Distance between destinations (standard distance[47]) or daily life centers
- D – Extent of clustering of minor activity locations around daily life centers[54]

III – The residential neighborhood in the overall activity space

- A – Extent of the self-drawn residential neighborhood
- B – Extent to which activity destinations are comprised in the self-drawn residential neighborhood or in fixed-radius street-network residential buffers
- C – Relative indicators comparing residential environment characteristics to non-residential environment characteristics
- D – Comparison of the effectively used resources to the resources available from the residence

IV – Summary typologies characterizing individual patterns of mobility, e.g., through the application of cluster analysis to numerous spatial behavior variables

[a]All of the indicators described in the present Table can be defined with the VERITAS-RECORD data.

Table 3. Summary of decisions/options related to the assessment of multi-place environmental exposures

I – Collection of raw locational information

- A – Data collection tool: survey of regular destinations, GPS tracking, travel diary over few days
- B – Data available
  - 1 – Geocoding at the area level → area-level information
  - 2 – Assessment of experienced or perceived neighborhood → area-level information (calculation of exposure in step IV without any preliminary transformation)
  - 3 – Collection of activity locations → point data
  - 4 – Collection of activity locations and imputation of shortest paths → point and linear data (determination of *shortest path network areas* in step III)
  - 5 – Collection of activity locations and travel paths → point and linear data (determination of *travel path network areas* in step III)[a]
  - 6 – Collection of chronological activity locations, travel paths, and time constraints → point and linear data (determination of *daily potential path areas* in step III)[a]

II – Selection of locational information

- A – To minimize confounding from selective daily mobility:
  - 1 – Exclude activity places visited for the behavior of interest
  - 2 – Only retain major/minor spatial anchor points
- B – Remove from locational data routes traveled by transportation modes that hinder contact with the environment (e.g., underground trains or subways)[a]

III – Transformation: deriving a spatial basis of measurement

- A – Overall convex activity space polygons: likely inappropriate
- B – Measurement in travel and activity place network areas
  - 1 – Simple buffering of raw locational information
    - a – Type of buffering: straight-line or road-network distance, time of access, etc.
    - b – Radius size depending:
      - - on the nature of and frequency of visit to each component of the route and activity place network
      - - on the environmental resource/exposure to measure
      - - on individual characteristics (e.g., with shorter radiuses for low-mobility individuals[12,62])
      - - on the study territory
      - - on the health outcome

- on whether a measure of potential or effective contact is of interest

2 – Kernel density estimation to derive measurement areas on the basis of a certain threshold in the intensity of frequenting (as determined from the distance from individual spatial locations and frequencies of visit of these locations)[45]

3 – Clustering techniques applied to the raw locational information to derive measurement areas (e.g., spatial scan statistics)[63]

IV – Algorithm for the calculation of exposure

A – Operator to apply (e.g., average exposure, minimal exposure, maximal exposure[12])

B – Cumulative environmental exposure or separate variables for residential and non-residential exposures

C – Weighting function: according to distance from participants' locations, proportional to the frequency of visit, dependent on travel speed and type of transportation mode,[64,a] etc.

[a]Refers to data that were not collected and approaches that cannot be implemented with the RECORD Study version of VERITAS.