The "Residential" Effect Fallacy in Neighborhood and Health Studies: Formal Definition, Empirical Identification, and Correction

Basile Chaix, Dustin Duncan, Julie Vallée, Anne Vernez-Moudon, Tarik Benmarhnia, Yan Kestens

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Basile Chaix,[a,b] Dustin Duncan,[c] Julie Vallée,[d] Anne Vernez-Moudon,[e] Tarik Benmarhnia,[f] Yan Kestens[g]

From:

[a]Inserm, UMR-S 1136, Pierre Louis Institute of Epidemiology and Public Health, Nemesis team, Paris, France;

[b]Sorbonne Universités, UPMC Univ Paris 06, UMR-S 1136, Pierre Louis Institute of Epidemiology and Public Health, Nemesis team, Paris, France;

[c]Department of Population Health, New York University School of Medicine, New York, NY, USA

[d]UMR Géographie-Cités, CNRS, Paris, France

[e]Department of Urban Design and Planning, Urban Form Lab, University of Washington, Seattle, WA, USA

[f]Department of Family Medicine and Public Health & Scripps Institution of Oceanography, University of California, San Diego, La Jolla, USA

[g]Department of Social and Preventive Medicine, University of Montreal, Montreal, Quebec, Canada

Correspondence: Basile Chaix, UMR-S 1136, Pierre Louis Institute of Epidemiology and Public Health, Faculté de Médecine Saint-Antoine, 27 rue Chaligny, 75012 Paris, France. e-mail: basile.chaix@iplesp.upmc.fr.

Running head: The "residential" effect fallacy

Background

Due to confounding from macro-organizations of territories and resulting correlation between residential and nonresidential exposures, classically estimated residential neighborhood-outcome associations capture nonresidential environment effects, overestimating residential intervention effects. Our study diagnosed and corrected this "residential" effect fallacy bias applicable to a large fraction of neighborhood and health studies.

Methods

Our empirical application investigated the effect that hypothetical interventions raising the residential number of services to 200, 500, or 1000 would have on the probability that a trip is walked. Using GPS tracking and mobility surveys over 7 days (227 participants, 7440 trips; Paris region, 2012–2013), we used a multilevel linear probability model estimating the trip-level association between the residential number of services and walking to derive a naïve intervention effect estimate; and a corrected model accounting for residential, trip origin, and trip destination numbers of services to determine a corrected intervention effect estimate (true effect conditional on assumptions).

Results

There was a strong correlation in service densities between the residential neighborhood and nonresidential places. From the naïve model, hypothetical interventions raising the residential number of services to 200, 500, and 1000 were associated with an increase by 0.020, 0.055, and 0.109 of the probability of walking in the intervention groups. Corrected estimates were of 0.007, 0.019, and 0.039. Thus, naïve estimates were overestimated by multiplicative factors of 3.0, 2.9, and 2.8.

Conclusions

Commonly estimated residential intervention-outcome associations substantially overestimate true effects. Our paradox-like conclusion is that, to estimate residential effects, investigators critically need information on nonresidential places visited.

INTRODUCTION

The present study contributes to the identification and correction of biases due to which commonly estimated associations between neighborhood characteristics and health/behavioral outcomes do not reflect causal neighborhood effects. Classical residential neighborhood studies use regression models to correlate residential exposures with overall health/behavioral outcomes (e.g., cumulating behavior inside and outside the residential neighborhood)[1-4] in order to quantify residential intervention effects. Among the assumptions that need to be met for such associations to represent the target causal effects (see the first section of eAppendix 1 for a tentative overview of these conditions), the counterfactual framework requires the absence of confounding. With confounding, unmeasured factors causally influence both the exposure and the outcome or determinants of the exposure and outcome, threatening the exchangeability between exposure groups required to validly estimate causal effects.[5] To improve the quality of causal inference, the present study aims to describe, diagnose, and correct a major confounding bias applicable to a large fraction of neighborhood and health studies. Surprisingly, this bias has received almost no attention in the literature (eAppendix 2). This source of bias has the major implication that residential neighborhood-outcome associations as commonly estimated may substantially overestimate the effects that residential interventions would have on the health of residents.

Recently scholars have suggested that environmental exposures in the multiple places visited by people may influence health beyond residential neighborhood exposures.[6-10] The source of the "residential" effect fallacy described here is that for many exposures, residential characteristics may be correlated with those of the multiple contexts visited during the daily activities (within-individual correlation), due to a common causal antecedent (see Figure 1).[11,12] Consequently, associations between residential neighborhood and health outcomes as classically estimated may capture some of the effect that nonresidential environments visited may have on behaviors and

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health (confounding of residential neighborhood–health associations, used for quantifying residential intervention impacts, by nonresidential effects). The "residential" effect fallacy implies that, because of the correlation between residential and nonresidential characteristics and resulting confounding, intervening on the residential neighborhood may not have the effect expected from classically estimated residential neighborhood–health associations.

As an empirical illustration, the present study relied on GPS tracking and on a mobility survey to precisely assess places visited over 7 days.[8,13,14] The resulting ability to disentangle truly residential from nonresidential effects allowed us to demonstrate the existence of a major generator of confounding that we refer to as the "residential" effect fallacy (we use quotes to put into question the residential nature of the underlying effect), quantify its magnitude, and correct for it. As an illustration, we focus on the well-known hypothesis that the residential accessibility to services fosters transport walking.[1,15-17].

METHODS

Data collection and processing

Population

The RECORD Study participants, recruited during preventive health checkups, were born in 1928–1978 and were residing at baseline in 112 municipalities of the Paris Ile-de-France region.[18-23] During the second study wave, 410 participants were invited to enter the RECORD GPS Study (approved by the French Data Protection Authority) in 2012–2013.[13] Of these, 247 accepted to participate and signed an informed consent form. Nine participants withdrew from the study and data were incomplete for four participants, resulting in a final completion rate of 57.1% (N = 234). Seven participants who either lived or spent the 7-day follow-up outside the Île-de-France region were discarded. Overall, 227 participants were included.

GPS-based mobility survey

Participants wore a QStarz BT-Q1000XT GPS receiver[24] on the right hip for the recruitment day and 7 additional days and filled a travel diary. GPS data (one point every 5 seconds) were processed by an ArcInfo 10 Python script (*www.spherelab.org/tools*).[25] It identified the places visited by participants (stationary locations) over the data collection period. The algorithm calculates a kernel density surface from the set of GPS points for each participant, extracts peaks as potentially visited locations, derives a timetable of all visits (of at least 10 minutes) over the period to each detected location with their start and end times, and uploads this information in the Mobility Web Mapping application.

The telephone prompted recall mobility survey[13,17] was based on this web mapping application.[13] With the participant, using the travel diary, the survey operator confirmed each of the detected visits to places (where participants fulfill functions) and corresponding trips, geolocated visits to places undetected by the GPS receiver or algorithm (e.g., very short visits), and modified/removed inaccurate/incorrect visits to places. For each visited place, participants reported the type of activity practiced at the location and the transport modes to reach the place. A SAS program generated the succession of visited places and trips between places with their start/end times.[13] Over 7 days, the 227 participants made 7440 (potentially multimodal) trips between places.

Measures

Walking

Based on the survey, a trip-level binary outcome was set to 1 (vs. 0) if only walking was used in the trip (partly walked trips also using, e.g., public transport coded as non-walking trips).

Individual covariates

Age (three categories: 35–49; 50–64; ≥65 years) and gender were considered. Marital status was coded as living alone or in a couple. Education was coded in four categories: no education, primary education, or lower secondary education; higher secondary education and lower tertiary education; intermediate tertiary education; and upper tertiary education. Household income per consumption unit was coded in three categories using the tertiles. Employment status was categorized in four classes: stable job; unstable/precarious job; unemployed; and other.

As neighborhood selection factors,[6,26] participants were asked whether, before moving to their current residence, when they were looking for a neighborhood to live, they found it important to live in a neighborhood (i) with good access to public transport and (ii) with enough services and facilities.[17] Each item was coded in three categories.

Modes in previous trips

Modes used in previous trips are a major confounder for the association between the trip-level service accessibility and walking.[17] Relying on a car in the previous trip influences both the environment visited and the mode in the next trip. For each trip, we counted the number of trips done since the last visit at home or in an alternative residence. A binary variable indicated whether a bike was used in one of these previous trips. A three-category variable indicated whether a personal motorized vehicle was used in none, some, or all of these previous trips.

Environmental measures

The spatial accessibility to services was computed within street network buffers (radius = 1 km, corresponding to a 10-to-15 minute walk[27-29]) centered on the departure and arrival of each trip

and on the residence (ArcInfo 10.0, Network Analyst). Using the Permanent Database of Facilities (Insee, 2011), we calculated the number of services of all types (public services, shops, entertainment facilities, etc.; see detail in eAppendix 3) in each buffer.

As illustrated in Figure 2, we calculated the percentage of each trip origin buffer and of each trip destination buffer that overlapped the residential buffer. When the percentage of overlap was $0 < X < 100$, we calculated separately the number of services in the part of the trip origin/destination buffer that overlapped and in the part that did not overlapped the residential buffer.

Statistical analysis and calculations

Analytic sample

We excluded episodes at activity places, yielding a sample of trips. Regression analyses excluded the following trips from the full sample (n = 7440): trips >4 km of length as non-easily walkable (n = 2597); atypical trips (professional tours, etc.) (n = 3); and trips starting and/or ending outside the Ile-de-France region (n = 207). The analytical sample comprised 4633 trips.

Correlation in service accessibility between residential and nonresidential neighborhoods

This correlation is a consequence of the causal structure in Figure 1 and the potential vector of the "residential" effect fallacy. We estimated a multilevel linear regression model with a random effect at the individual level to investigate the relationship between the density of services per km² in the residential buffer (explanatory variable) and the density of services in the trip origin buffer (outcome). Trips starting at the residence were removed from this regression database. Moreover, for trips whose origin buffer partly overlapped the residential buffer, we used as the outcome the density of services per km² in the portion of the trip origin buffer that did not overlap

the residential buffer (we used densities per km² in this analysis rather than counts of services as in the main analyses to deal with these portions of buffers). Interactions between the residential density of services and, on the one hand, the street network distance between the residence and the trip origin, and on the other hand the square of this distance (quadratic term), were specified.

General description of the approach

To mimic an intervention focused on poorly served neighborhoods, the hypothetical interventions examined are to raise the number of services accessible in the residential buffer to 200, 500, or 1000 if below that number.

We estimated regression models at the trip level (one observation per trip).[13,17] Variations in the probability of exclusively walking during a trip were modeled with linear probability models (binary variable, identity link). This model quantifies associations on the risk difference scale,[30] i.e., on the probability scale, which is particularly relevant to decision-making.[31] Multilevel models were used, with a random effect at the individual level, to account for the within-individual correlation in modal choice. Individual sociodemographic covariates and neighborhood selection factors were forced into the models.

Naïve estimate of the residential intervention effect

The model based on trip-level data to calculate the naïve (biased) estimate of the intervention effect included sociodemographic variables, neighborhood selection factors, and the residential number of services (two continuous variables: linear and quadratic terms). Based on model coefficients, we calculated for each trip the predicted probability that it is entirely walked from all model covariates (including the number of services). This calculation was performed for the pre-intervention state and for each of the post-intervention scenarios (residential services raised

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to 200, 500, or 1000 if below that number). For each of these four cases, we calculated the average probability that a trip is walked across all individuals and trips. The intervention effect estimate was computed for each intervention level as the post-intervention average probability of entirely walking in a trip minus the pre-intervention probability, only among participants who experimented the hypothetical intervention (i.e., with less than 200, 500, or 1000 services).

Corrected estimate of the residential intervention effect

The corrected (unbiased) estimate (true intervention effect conditional on a number of conditions listed in eAppendix 1) was calculated from a model including sociodemographic variables, neighborhood selection factors, modes used in previous trips from home (confounder of the momentary environmental effect), the number of services at the departure and arrival of the trip (linear and quadratic terms), and the residential number of services (linear and quadratic terms). It is useful to also include the association between residential services and walking to capture (after adjustment for neighborhood selection factors) the influence of the residential accessibility to services on preferences and overall choice of mode (e.g., buying a car or relying on public transport) that may influence mode choice in all trips (even far from home). Associations with both the residential and trip origin/destination numbers of services are required to calculate the corrected intervention effect estimate.

The number of services in each trip origin or trip destination buffer was affected by the intervention only if the residential number of services was increased by the intervention and if the trip-origin/destination buffer overlapped the residential buffer. If services in the residential buffer were increased by N and if X% of the residential buffer was in the trip-origin/destination buffer, then the number of services in the trip-origin/destination buffer was increased by X% of N.

The regression equation and values of covariates (including for the pre- and post-interventional number of services in the residential, trip origin, and trip destination buffers) were used to calculate the probabilities that each trip is walked. The same approach than for the naïve estimate was used to calculate the corrected estimate for the different intervention levels for participants in the intervention group.

Assumptions made by this approach are discussed in the second section of eAppendix 1. All regression models were estimated with a Markov chain Monte Carlo approach using Winbugs.[32]

RESULTS

Descriptive data

Overall, 64.3% of the 4633 trips of 4 km or less were entirely walked. At the individual level (N = 227), the percentage of trips that were entirely walked varied from 0% to 100% (10th percentile: 18%; median: 67%; 90th percentile: 96%). The median number of services was of 613 in the residential neighborhood (10th percentile: 109; 90th percentile: 2992) and of 769 in the trip origin and trip destination buffers (10th percentile: 117; 90th percentile: 3389).

Figure 3 reports the magnitude of the association between the residential number of services and the trip origin number of services according to the street network distance between the residence and each trip origin. The association operated on a long range: even when the trip origin was 5 km away from the residence, an increase by 1000 in the residential number of services was associated with an increase of 656 services [95% credible interval (CrI): 487, 825)] in the trip origin buffer. The association vanished when the street network distance was >25 km.

Hypothetical scenarios of intervention

The three hypothetical scenarios of intervention are described in Table 1. For example, the intervention to raise the residential number of services to 200 would affect 58 participants (26%), corresponding to an increase in the number of services by 101 or more in 50% of the cases, and implying a reduction of the distance between services along streets from a median of 315 m to a median of 165 m in the intervention neighborhoods.

Naïve estimates of intervention effects

Based on the regression model reported in eAppendix 4, the probability to walk in a trip increased with the number of services in the residential neighborhood. As also shown in Figure 4 (panel A), there was a quadratic effect: increases in the number of services beyond 2000 were not associated with further gains in the probability that a trip is walked.

Based on this model, the hypothetical interventions to raise the residential number of services to 200, 500, and 1000 were associated with an increase by 0.020, 0.055, and 0.109 of the probability that a trip is walked for participants in the intervention groups (Table 2).

Corrected estimates of intervention effects

To derive the corrected intervention effect estimates, we ran the model reported in eAppendix 4 (adjusted for modes used in previous trips and for the trip origin/destination numbers of services). As also shown in Figure 4, the residential number of services was no longer associated with walking (panel B). While the trip origin number of services showed no relationship with walking (panel C), the probability that a trip is walked increased with the number of services around the trip destination (panel D). Again a quadratic effect indicated that the increase in walking

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associated with an increment of services at the trip destination tended to be lower when the base number of services was high.

Based on the corrected model, the hypothetical interventions to raise the residential number of services to 200, 500, and 1000 led to an increase by 0.007, 0.019, and 0.039 of the probability that a trip is walked for participants in the intervention groups (Table 2). Thus, the naïve estimates overestimated the corrected ones by multiplicative factors of 3.0, 2.9, and 2.8.

DISCUSSION

Contributing to the causal neighborhood effect literature, the present study empirically demonstrates that the "residential" effect fallacy, an overlooked and potentially widespread generator of confounding, was of considerable magnitude for the association between a residential pseudo-intervention on the number of services and walking. This study estimated an association corrected from the spurious contamination by correlated nonresidential effects.

Strengths and limitations

The primary strength of the present study is that it formally defined a bias, the "residential" effect fallacy, which, despite its general relevance for estimating causal neighborhood health effects, has received no formal consideration in the literature (eAppendix 2 reviews two studies[10,33] connected to the present topic but that did not explicitly investigate the bias). Second, this paper could rely on accurate trip-level data obtained through a complex protocol combining GPS tracking, algorithm processing, and related prompted recall survey.[8,13,17] The availability of data disaggregating the behavioral outcome at the level of the multiple places visited by the participants (in this study the different trips) allowed the empirical identification and correction of the bias, which would have otherwise been impossible. A third strength is our policy-relevant

specification of the target causal effect of services that was conceptualized in an interventional perspective (i.e., raising the access to services not by a constant value even in well-served neighborhoods but to a certain level if below that level). However, it should be kept in mind that this pseudo-intervention was not meant to mimic a completely plausible real-world intervention (whose area would not exactly match the precise home-centered buffers of specific individuals) but was seen as an intervention-like formulation of an observational effect estimate, an approach that we recommend for future observational neighborhood studies. As a fourth strength, eAppendix 5 shows that we were able, not only to quantify the magnitude of the "residential" effect fallacy bias, but also to recalculate the naïve estimate of the residential intervention effect based on an analytical understanding of the mechanism of bias (we could mimic the spurious transfer of nonresidential effects to the "residential characteristic"-walking association attributable to the confounding structure and correlation in the number of services).

Regarding limitations, as detailed in the second section of eAppendix 1, the present work did not consider that an increase in the number of services may also: (i) increase the number of trips and that a similar "residential" effect fallacy may bias this association; and (ii) affect the destinations and length of trips.

Interpretation of the empirical findings

Our data showed correlation in the local number of services between residential and nonresidential places over a long range of more than 20 km, supporting the causal structure in Figure 1 and creating a substantial potential for the "residential" effect fallacy.

In the adjusted model that was used to derive a corrected estimate of the residential intervention effect on walking (accounting for the residential, trip origin, and trip destination numbers of services), only the trip destination number of services was associated with walking.

This finding that trip destination characteristics are more influential than trip origin characteristics has already been reported.[34] A potential interpretation is that when constraints in mode choice at the beginning of the trip are taken into account (by controlling for the modes used in previous trips), the environmental conditions at the beginning of the trip loose their predictive importance, and only the spatial accessibility to services at the destination of the trip matters in the adoption or not of walking.

The major finding of our study is that the naïve effect estimates of the residential interventions of interest overestimated the true effects (true effects conditional on a number of assumptions listed in eAppendix 1) by a multiplicative factor of 3. Put the other way round, the correct estimates corresponded to only 35% of the naïve estimates. Clearly, the magnitude of this bias is very substantial compared to biases often documented in studies. The estimated intervention effect on transport walking was relatively modest, especially after applying the correction. Because of this carefully controlled correction and because we could recalculate the naïve intervention effect estimate based on the analytical understanding of the bias (eAppendix 5), we can confidently conclude that the bias of considerable magnitude that was documented was attributable to the "residential" effect fallacy. People travel to various places in their daily activities[35] and the influence of the service environment in these various nonresidential places on mode choice is spuriously incorporated in the residential effect estimate because of the intra-individual correlation in the exposure to services between residential and nonresidential places.

General implications

The severity of the "residential" effect fallacy, a phenomenon of nonresidential to residential association contamination, depends on the magnitude of confounding and resulting correlation between residential and nonresidential places in the exposure of interest (as influenced to a large

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extent by the spatial autocorrelation of the exposure over the territory). Because of the urbanization structure of territories and of the socioeconomic distribution of populations, the spatial accessibility to services exhibits a considerable spatial autocorrelation,[36] contributing to a correlation in services between residential and nonresidential neighborhoods visited. For the same reasons and other, many exposures of interest in neighborhood and health studies are likely spatially autocorrelated, such as neighborhood social stressors, fast-food restaurants, alcohol outlets, green spaces, or outdoor noise and air pollution.[11,12] Thus a considerable number of neighborhood or environmental studies exploring associations between residential characteristics and health/behavioral outcomes (cumulating outcome components inside and outside the neighborhood)[1-4] likely yielded substantially overestimated residential effects estimates (although the bias may be weaker for exposures showing a lower correlation between residential and nonresidential places). Regarding generalization, there is no particular reason why this bias would be of particular importance in France (the marked distinction between urban centers, suburbs, and the countryside and the socioeconomic stratification of territories is widespread across countries).

When studies consider that their residential exposure variable is an imperfect proxy of environmental exposures in the multiple activity places visited, they are not subject to the "residential" effect fallacy bias described in the present study; however, they are then subject to a severe measurement error because residential exposures are inaccurate proxies of activity space exposures.[7,37] As a consequence, classical residential neighborhood studies, depending on the interpretation of the estimated parameter, are either subject to the "residential" effect fallacy when the association is interpreted as a truly residential effect (due to the similarity between residential and nonresidential neighborhoods) or to measurement error when the association is interpreted as a total environmental effect (due to the dissimilarity between residential and

nonresidential neighborhoods, i.e., to the fact that residential neighborhood characteristics are poor proxies of nonresidential characteristics). These two sources of error are likely to be substantial. Readers are referred to eAppendix 6 for advanced interpretations of the "residential" effect fallacy and sensitivity analyses (e.g., for an estimation of the intervention effect under the assumption that participants are also affected by the intervention in the other participants' residential areas).

A critical implication of the "residential" effect fallacy is that interventions developed in a residential neighborhood will have a much lower impact on the behavior or health status of residents than would be expected based on the naïve association. In order to reach the impact expected from the estimated association, it would be necessary to intervene, not only in the residential neighborhood but also in various visited locations of the persons (whose impact is spuriously incorporated in the residential effect estimate), which is far more challenging and costly.

For studies without access to individual mobility data, calculation approaches could be developed to speculate on the magnitude of the "residential" effect fallacy based on knowledge of the spatial distribution of the exposure of interest around participants' residences and aggregated knowledge of local mobility patterns. However, the recommended strategy is obviously to collect detailed mobility data for each study participant to address both measurement error in environmental exposures and the "residential" effect fallacy. We suggest to rely on the present design, i.e., to follow participants over time and space, to accurately identify life segments that make up their daily life schedules, to identify momentary exposures in these life segments, and to disaggregate the behavioral outcomes (e.g., physical activity, smoking, alcohol consumption, or food consumption) usually assessed at the individual level at the level of these multiple space-time segments of the days.[17] This methodology will allow investigators to disentangle true

residential influences from nonresidential effects that otherwise confound the residential

intervention effect estimates of interest. Overall, our key paradox-like message is that to properly

investigate residential effects, investigators critically need data on the nonresidential places

visited.

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Figure 1

Directed acyclic graph representing the confounding structure of the "residential" effect fallacy bias with an open backdoor path from the residential exposure to the nonresidential exposure through the macro-organization of the territory. Such macro-organization generates similarity between residential and nonresidential exposures, as modulated however in a complex way by a rich set of determinants of individual mobility. Given the unpredictable way how the macro-organization of the territory and the determinants of individual mobility jointly influence the degree of similarity / dissimilarity between residential and nonresidential exposures, the most straightforward option to close the backdoor path is to directly geocode the nonresidential environments visited and assess related exposures to neutralize confounding.

Figure 2

Illustrative example of two successive trips for a given individual, from the residence (A) to a first visited place (B), and to a second visited place (C). Buffers (1 km street radius) are drawn around each place. The darker buffer represents the residential buffer. For the three successive buffers at visited places, the percentage of overlap with the residential buffer is respectively 100% (A), 30% (B), and 0% (C). The number of services accessible within each 1 km radius buffer was calculated. For the buffer of place B (0 < % overlap < 100) but not for the other buffers, we also calculated the number of services accessible within the portion of the buffer overlapping and not overlapping the residential buffer.
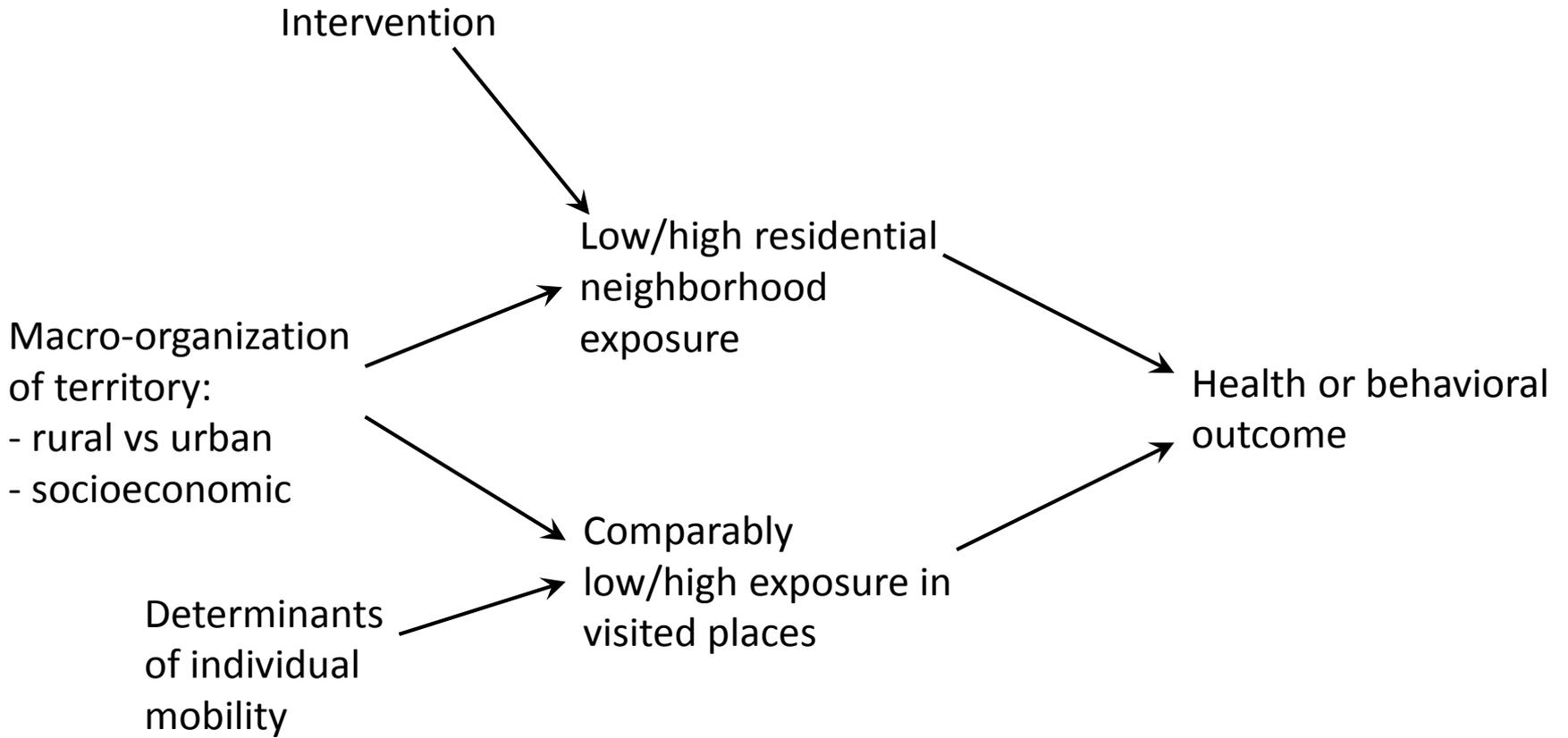
Figure 3

Association between the residential density of services per km² and the trip origin density of services per km² according to the street network distance between the residence and the trip

origin (modeled among 3155 trip origins after excluding trips starting at the residence). For example, an increase by 1000 of the residential density of services was associated with an increase by 619 of the number of services per km² around trip origins located 10 km away from the residence (overall Pearson correlation between residential and trip origin densities of services for trip origins located less than 10 km away from the residence = 0.27; 95% confidence interval: 0.23, 0.30).

Figure 4

Increase in the probability that a trip is walked associated with changes in the number of services in the residential neighborhood [naïve estimate model (A) and corrected estimate model (B)], with the trip origin number of services [corrected estimate model (C)], and with the trip destination number of services [corrected estimate model (D)] (number of services = 0 as the reference).
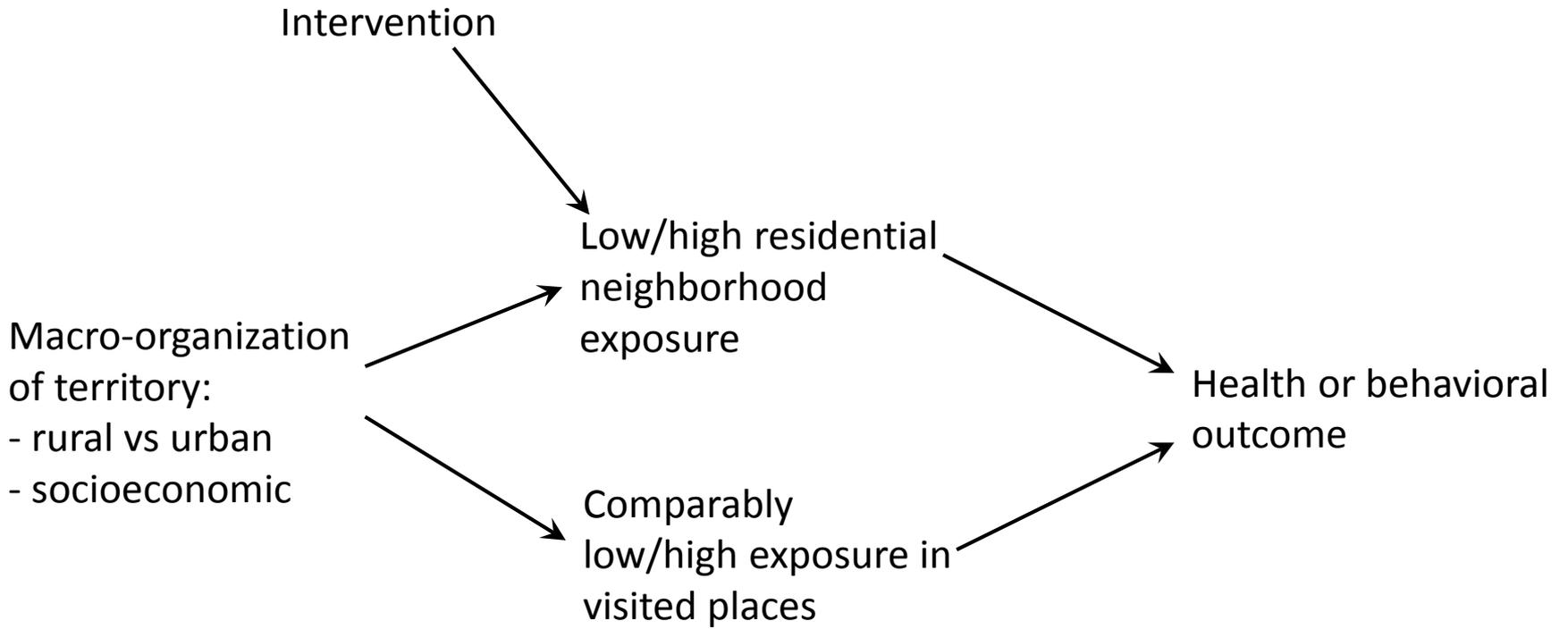
Intervention
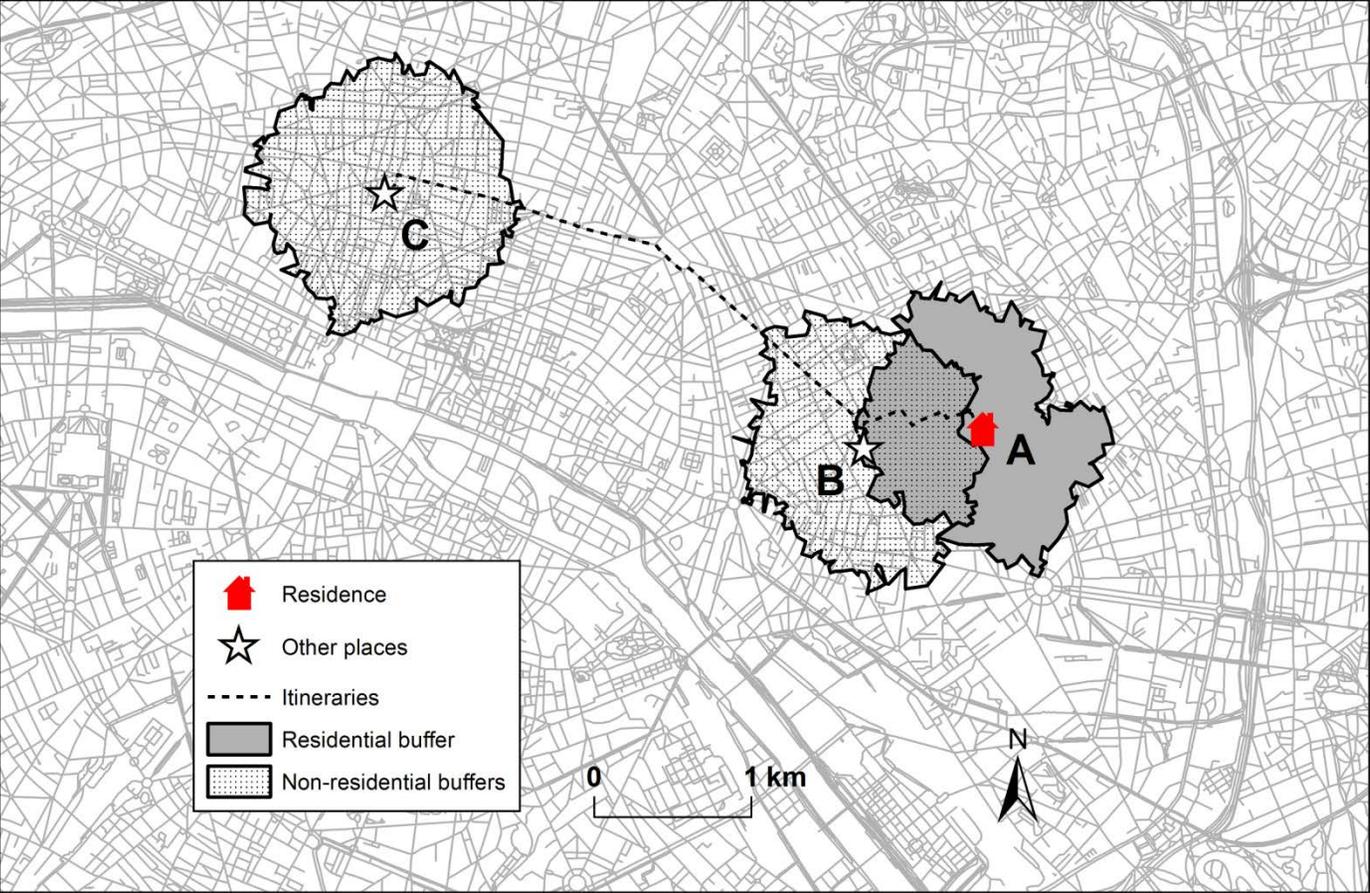
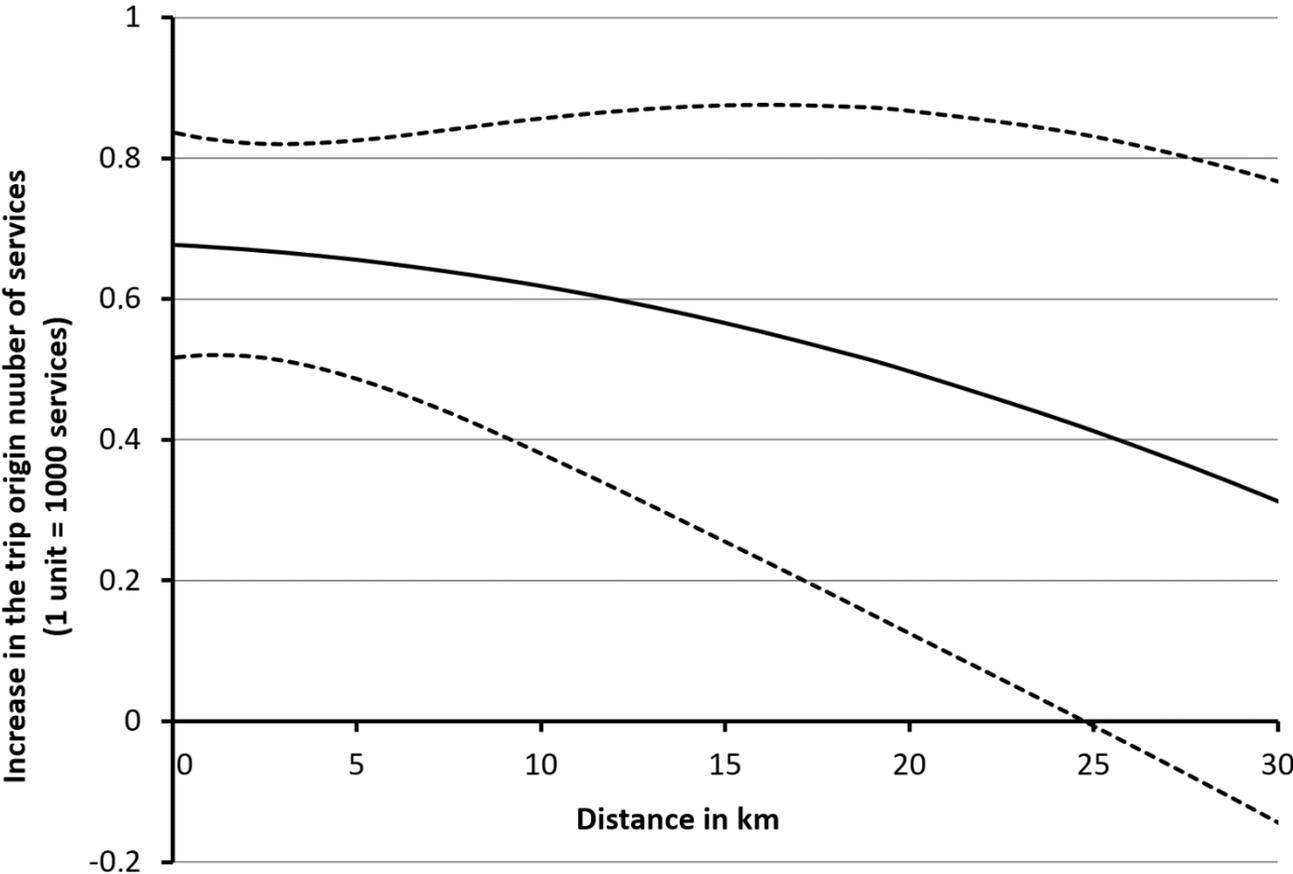Macro-organization
of territory:
- rural vs urban
- socioeconomic

Low/high residential
neighborhood
exposure

Comparably
low/high exposure in
visited places

Health or behavioral
outcome

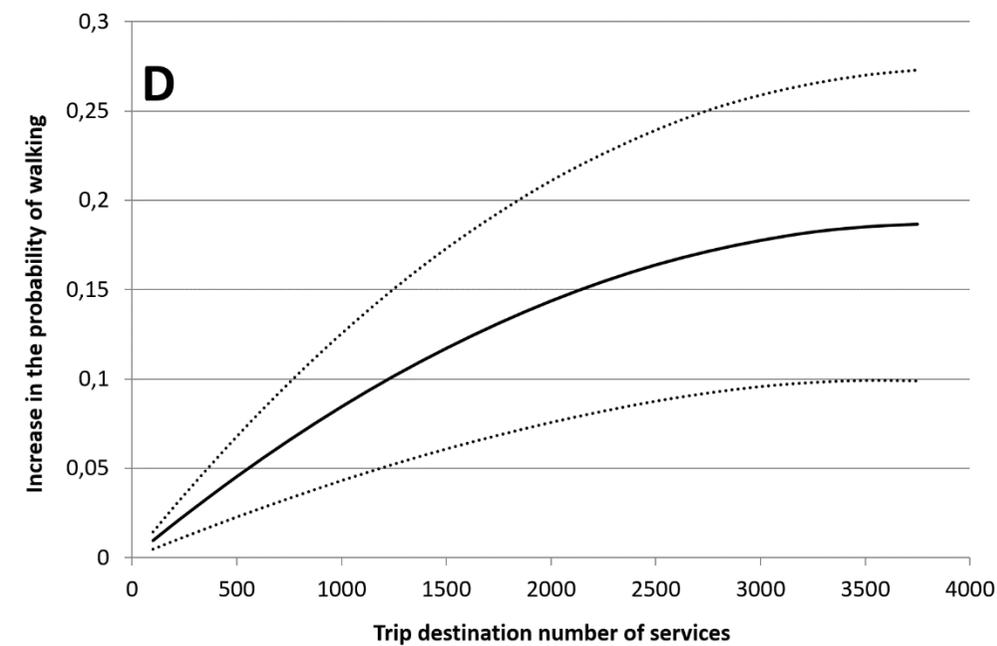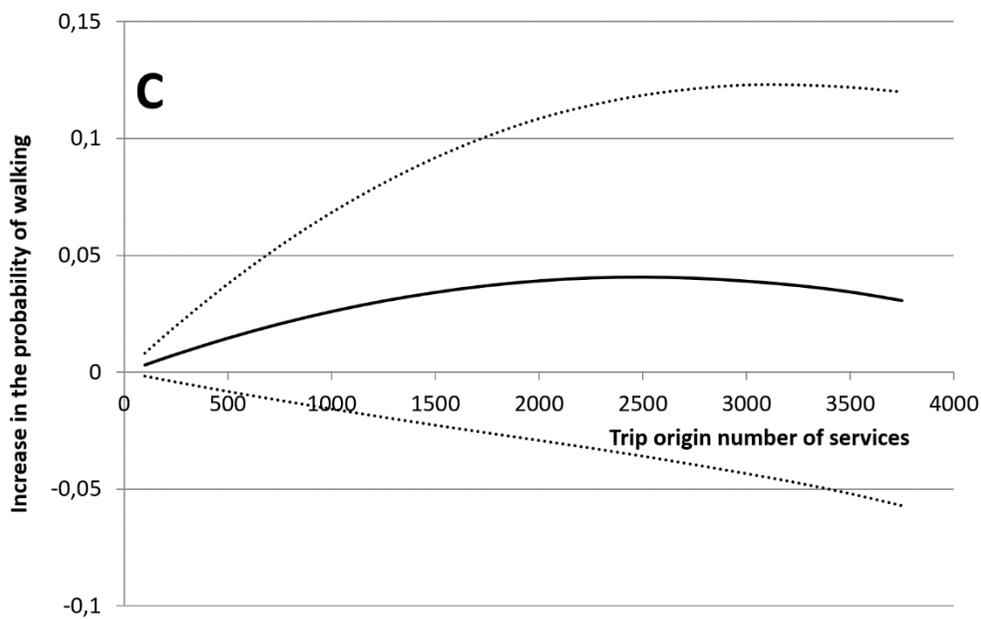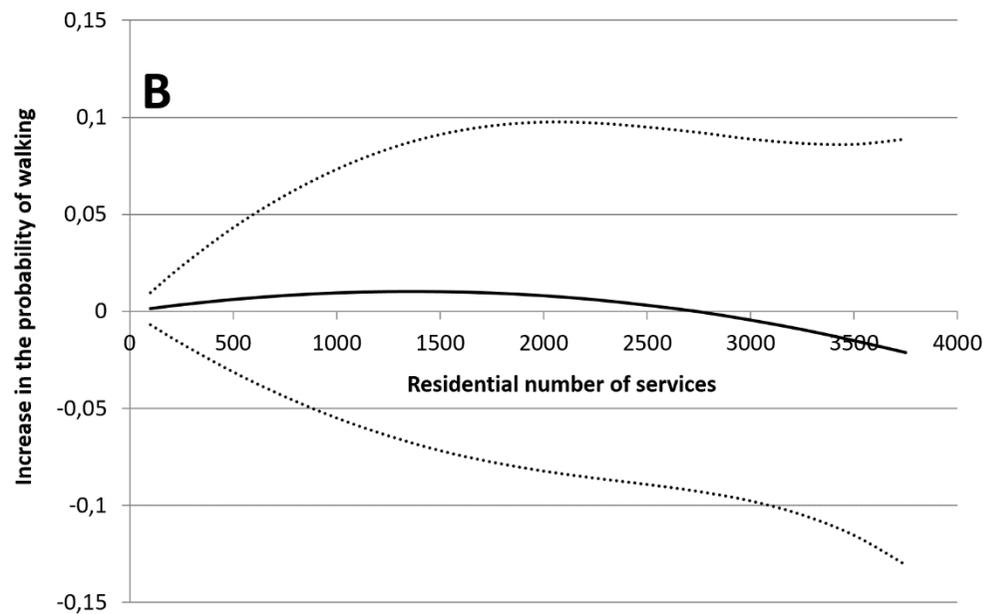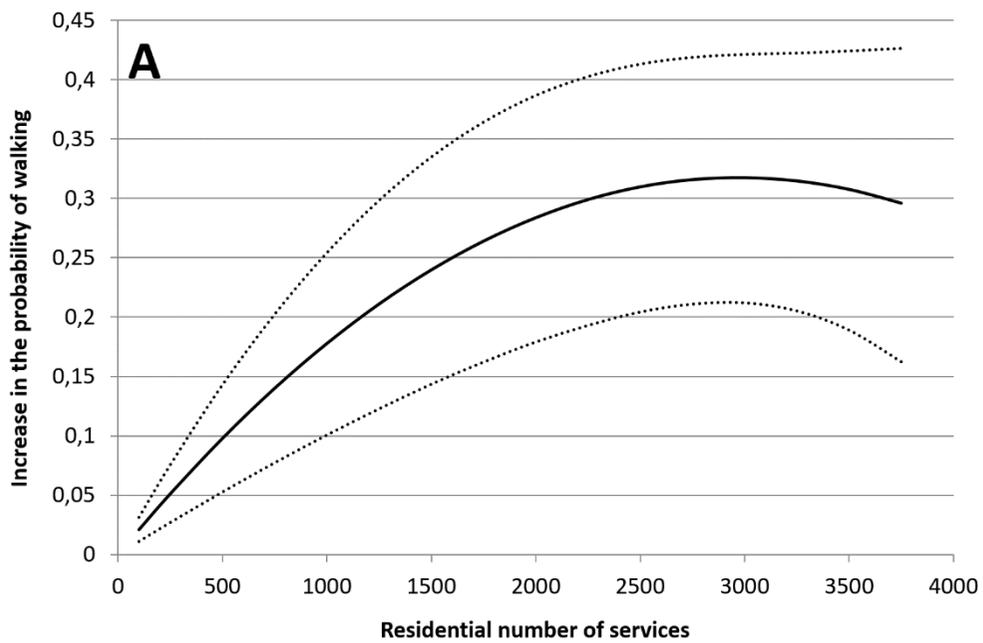**Figure 2**

Figure 3

Figure 4

Table 1. Description of the hypothetical scenarios of intervention on the number of services in the residential neighborhood

Number of services increased to…	Number of participants affected	Increase in the number of services in intervention neighborhoods Median (10th and 90th percentiles)	Distance in m along streets between services in intervention neighborhoods, before the intervention[a] Median (10th and 90th percentiles)	Distance in m along streets between services in intervention neighborhoods, after the intervention[a] Median (10th and 90th percentiles)
200	58	101 (14, 173)	315 (193, 813)	165 (110, 218)
500	116	297 (92, 452)	194 (96, 606)	74 (53, 92)
1000	159	735 (183, 947)	136 (55, 488)	38 (29, 50)

[a]The calculation of distance between services along streets combines services on both sides of the street (a service on the left side followed by another service 20 m after on the right side of the road correspond to a distance of 20 m between services). Dual carriageways, however, intervene as two separate streets in the calculation. Non walkable highways and speedways are not accounted for in this calculation.

Table 2. Naïve and corrected estimates of the hypothetical intervention effect of raising the number of services in the residential neighborhood to 200, 500, or 1000 for participants in the intervention groups (i.e., with a residential number of services below 200, 500, or 1000)[a]

	Intervention: residential number of services raised to 200	Intervention: residential number of services raised to 500	Intervention: residential number of services raised to 1000
Naïve estimate	0.020 (0.010, 0.029)	0.055 (0.030, 0.079)	0.109 (0.063, 0.154)
Corrected estimate	0.007 (0.001, 0.014)	0.019 (0.000, 0.038)	0.039 (0.004, 0.073)

[a]The exact sets of predictors included in the naïve estimate model and in the corrected estimate model are reported in Supplementary Table 1. The intervention effect is expressed on the probability scale.

eAppendix

The "residential" effect fallacy in neighborhood and health studies: formal definition, empirical identification, and correction

eAppendix

eAppendix 1: Assumptions required for estimating a valid causal residential intervention effect

In this paper, we aimed to estimate the causal effect of a hypothetical intervention raising the residential number of services on the probability that a trip is walked. There are potential concerns about drawing causal inferences based on our estimate, even after the correction of the "residential" effect fallacy. Below, we provide a tentative list of assumptions that would need to be met so that the estimate of the residential intervention effect corrected from the "residential" effect fallacy represents the causal intervention effect.

1) Estimation of the regression model used for the calculation

- We assume no systematic measurement error in the probability that a trip is walked according to the exposure variable (the residential accessibility to services).

- We assume no systematic measurement error in the number of services across the different types of transport modes (e.g., differential misclassification of the count of services according to the type of place, itself associated with a particular mode use).

- We assume no systematic nondifferential measurement error in the number of services (i.e., a uniform decrease or increase in the count of services), which would bias the intervention effect estimate due to the nonlinear relationship between the number of services and walking.

- Also we make the assumption of no random measurement error in the number of services (i.e., the exposure) which, as a regression dilution bias, would result in an attenuation towards the null of the association between the exposure to services and the probability that a trip is walked.

- We assume no random measurement error in the transport outcome, which would increase the standard error of the estimated association.

- The study examined the association between the number of services in a 1 km radius buffer around the residence and walking. This was not considered to be an assumption of the study (that would be related to the expected spatial scale of this causal determinant of walking), but to be a logical consequence of the hypothetical choice of policymakers to intervene within 1 km of the residence of a number of residents. However, when we attempted to estimate the causal effect of the number of services around the trip origins and destinations, we also chose a 1 km radius for the trip origin/destination buffers for the sake of coherence. This was related to the assumption that the causal effect that we attempted to take into account (as a potential confounder of the intervention effect) was best captured with a radius of 1 km. It might be that the optimal radius to capture this effect is shorter. However, this is likely not of critical importance due to the strong autocorrelation in the number of services that should minimize the impact of small differences in the radius to define the buffers.

- We assume that there is no selection bias in the sample used for estimating the association of interest. Specifically, we assume that the participation in the sample is not influenced by both the exposure (or a determinant of the exposure) and the outcome (or a determinant of the outcome).

- We assume that there is no additional unmeasured trip-level, individual-level, or environmental confounders in the relationship between the residential number of services and the probability of walking, after our correction of the "residential" effect fallacy and after accounting for neighborhood preferences at the time of moving in one's current neighborhood (neighborhood selection factors) and the other covariates. We assume that residents of neighborhoods with different levels of spatial accessibility to services are otherwise exchangeable conditional on adjustment factors.

- We assume that the positivity assumption (or experimental treatment assignment assumption) is held. We assume that there are both exposed and unexposed individuals at every combination of levels of the observed confounders in the population of interest. Under this assumption, our regression modeling is not based on excessive extrapolations.

- The random effect linear probability model including linear and quadratic terms for the service accessibility variables is assumed to be not misspecified. The following standard assumptions are hypothesized to apply: homoscedasticity; normal distribution of residuals at the trip level and at the individual level; and absence of correlation between the exposure of interest or other covariates and the level-2 individual-level random intercept.

2) Calculation of the residential intervention effect estimate based on the regression estimates

- The method acknowledges that the residential intervention may also influence mode choice in trips far from the residence through the influence that the residential neighborhood has on the overall choice of mode (e.g., buying a car or a public transport pass). This is not an assumption that we force into the model, but a potential mechanism that is allowed for in the model and that is incorporated into the calculation only if estimated to be at play.

- We assume that there is no relevant time varying environmental variable correlated with the implementation of the intervention of interest. For example, if interventions aiming at increasing the number of services were systematically implemented simultaneously with urban design changes (i.e., if the two were consubstantial), the true, pure intervention effect would not correspond to the one estimated in this study.

- Provided that the assumptions listed above are satisfied, the regression estimates reflect average causal effects of the number of services in the residential, trip level,

and trip origin neighborhoods on walking. However, these causal effects are averages of heterogeneous effects across different population subgroups. Our calculation assumes that the various neighborhoods in our study territory contain a comparable mix of heterogeneous residents leading to a uniform intervention effect on walking.

- We make the assumption that the intervention (increase in the number of services) is evenly distributed over the 1 km residential buffer; thus the portion of the residential intervention that affects a participant located in a nonresidential place depends on the fraction of the residential buffer that is included in this nonresidential buffer.

- The calculation of the residential intervention effect estimate was based, among other, on the estimated associations between the trip origin/trip destination numbers of services and walking. These were average effects, i.e., the associations between the trip origin or trip destination number of services and walking were estimated accounting for all trip origins and destinations in the database. However, this estimate was used to calculate the intervention effect estimate for trip origins and destinations close to the residence (as their buffer had to overlap the residential buffer). Thus we hypothesize that the estimated associations between the trip origin/destination numbers of services and walking were appropriate to estimate the intervention effect for trip origins/destinations overlapping the residential buffer.

- In the calculation of the overall intervention effect estimate based on the regression estimates, an absence of residential migration between the pre-intervention and post-intervention states is assumed. Also, we assume no change in the places visited for this calculation. Regarding the notion of post-intervention disequilibria, our calculation is based on the stable unit treatment assumption, i.e., the intervention implemented for one person does not affect the level of intervention for another person. While this assumption was made in the calculations in the main article, the last section of

eAppendix 7 provides calculations relaxing this assumption of an absence of interferences between participants.

- It should be noted that the present work took into account the "residential" effect fallacy only in the association of services with the probability that a trip is walked. However, our calculations did not account for the fact that an increase in the residential number of services may also increase the number of trips, and that a similar "residential" effect fallacy may bias this association. Correcting for the "residential" effect fallacy in the number of trips would be more complicated.

- Moreover, an intervention on services in the residential neighborhood may affect not only the number of trips but also the length of trips and how trip origins / destinations are close or not from the residence.[1] Because our regression models were purposely not adjusted for distance, the association estimated between services and walking may operate through a switch of mode in a given trip with fixed start and end points but also through a switch from a longer motorized trip to a shorter walking trip. However, our estimation of the intervention effect did not allow for a change in the extent to which the origin and destination buffers of each trip overlapped the residential neighborhood. This is a limitation since an intervention raising the residential number of services may increase the percentage of trips whose origin and/or destination buffers overlap the residential neighborhood. Thus our illustrative study was to some extent grounded on the simplifying hypothesis that participants would anyway visit all the places visited during the follow-up even if the residential number of services was increased.

eAppendix 2: Review of previous literature

There are very few articles in the whole literature on neighborhood / environmental effects on health that relate at least approximately to the topic of the "residential" effect fallacy bias that we describe.

Inagami et al.

In a well-known article,[2] Inagami and colleagues found that a low socioeconomic status of the residential neighborhood was associated with a worst self-rated health; that exposure to a low socioeconomic status in nonresidential neighborhoods was associated with a worst self-rated health (only in some of the models); and that adding the nonresidential term to the model increased the residential effect estimate. Thus the standard calculation of the residential effect estimate led to an underestimation of the supposedly true residential effect, i.e., the confounding bias was in the form of a suppression effect rather than an amplification effect as in our article.

However, the conceptual and analytical framework of Inagami and colleagues was entirely different from ours. In the work of Inagami, the nonresidential exposure variable was calculated as the difference between the nonresidential exposure and the residential exposure, thus expressed as nonresidential relative disadvantage. First, it should be noted that such a "relative exposure effect" is an original effect in itself, distinct from the effect of the absolute level of nonresidential exposure we are interested in. Indeed, such a relative exposure specification likely captures a different effect operating through distinct mechanisms, such as the influence of cognitive processes of comparison of residential and nonresidential neighborhoods. Second, Inagami and colleagues implicitly recognize that there was a positive correlation between the absolute socioeconomic status in the residential and nonresidential

neighborhoods (Data and methods, Measures, Operationalizing non-residential neighborhood exposure, fourth paragraph). However, the suppression effect of confounding documented by Inagami (rather than amplification effect in our case) implies a negative correlation between the residential socioeconomic status and nonresidential socioeconomic exposure variable (as opposed to a positive correlation in our "residential" effect fallacy application). This negative correlation stems from the relative definition of the nonresidential exposure that was used (difference with the residential exposure) and may be attributable to a "regression to the mean", i.e., to the fact that participants with a particularly high residential socioeconomic status will often have nonresidential places with a comparably lower socioeconomic status (thus a negative relative exposure) while participants with a particularly low residential socioeconomic status will often have nonresidential places with a comparably higher socioeconomic status.

Overall, the study by Inagami and colleagues investigates how a nonresidential effect defined in a different way than the residential effect (relative exposure) negatively confounds the residential effect of interest. Differently, our study investigates how a nonresidential effect defined in a similar way than the residential effect positively confounds the residential effect. Thus our study is the first to address the "residential" effect fallacy bias described here.

Sharp et al.

Another article by Sharp and colleagues[3] based on longitudinal data from the same cohort than in the Inagami article examined the extent to which controlling for the exposure to nonresidential neighborhood disadvantage affected the relationship between residential neighborhood disadvantage and self-rated health. As opposed to Inagami et al., nonresidential disadvantage was assessed in absolute rather than relative terms. The work by Sharp and colleagues reported that the residential effect estimate was slightly attenuated when the model

was adjusted for nonresidential exposures. This reduction of the strength of the association was attributed to a mediation of the residential association by the nonresidential term, although no concrete description of the causal mechanism involved in this supposed mediation and no explanation based on directed acyclic graphs of why this should be mediation rather than confounding were provided. Even if the observed reduction in the residential association when controlling for the nonresidential term is coherent with our own findings, the conceptual framework that we develop is substantially different. Although we acknowledge that nonresidential exposures mediate to some extent the estimated residential neighborhood-walking association (the residential environment influences the transport modes used, which influence the types of places visited), we emphasize that most importantly, nonresidential exposures confound the residential neighborhood-walking association.

eAppendix 3: Services accounted for in our spatial accessibility variable

Consistent with previous literature,[4-6] the spatial accessibility to destinations within a walking distance has been found to be a major determinant of both transport and recreational walking in our RECORD Study.[7-9] Services, especially because a large spectrum of them were accounted for in our study, represent a large share of the potential destinations of participants. Thus, our variable is expected to capture in a relatively reliable way a factor that has a direct causal effect on the likelihood of transport walking.

   We report below the list of services accounted for in our variable of spatial accessibility to services. Although neither sport facilities nor parks were taken into account in the list of services that was analyzed, it can be seen that a large fraction of the services available were included in this study.

List of services analyzed:
A101 – Police
A102 – Treasury
A103 – National Employment Agency
A104 – Gendarmerie
A203 – Bank
A206 – Post office
A207 – Package delivery point
A208 – Municipality post office
A301 – Car repair
A302 – Automobile technical inspection service
A303 – Car rental
A401 – Mason
A402 – Plasterer, painter
A403 – Wood worker, carpenter, locksmith
A404 – Plumber, roofer, heating engineer
A405 – Electrician
A406 – Construction company
A501 – Hairdresser
A502 – Veterinarian
A504 – Restaurant
A505 – Real estate agency
A506 – Laundry
A507 – Beauty care

B101 – Hypermarket
B102 – Supermarket
B103 – Large do-it-yourself store
B201 – Minimarket
B202 – Grocery
B203 – Bakery
B204 – Butcher / delicatessen shop
B205 – Frozen food store
B206 – Fish market
B301 – Bookshop, stationery store
B302 – Clothing store
B303 – Home equipment store
B304 – Shoe store
B305 – Home appliance store
B306 – Furniture store
B307 – Sports store
B308 – Wallpaper and wall covering store
B309 – Drugstore, hardware, handiwork
B310 – Perfumery
B311 – Watch and jewellery
B312 – Florist
B313 – Optical store
D108 – Health center
D201 – General practitioner
D202 – Cardiologist
D203 – Dermatology and venereology
D204 – Medical gynecology
D205 – Gynecology obstetrics
D206 – Gastroenterology
D207 – Psychiatry
D208 – Ophthalmology
D209 – Otorhinolaryngology
D210 – Pediatrics
D211 – Pulmonology
D212 – Diagnostic radiology and medical imaging
D213 – Stomatology
D221 – Dental surgeon
D231 – Midwife
D232 – Nurse
D233 – Masseur physiotherapist
D235 – Speech therapist
D236 – Orthoptist
D237 – Chiropodist
D238 – Audioprosthesist
D239 – Occupational therapist
D240 – Psychomotrician
D241 – Medical radiology operator
D301 – Pharmacy
D302 – Medical analysis laboratory
F301 – Cinema

F302 – Theater

eAppendix 4: Regression models estimated to determine the naïve and corrected intervention effect estimates

eAppendix Table 1. Regression models estimated to determine the naïve and corrected residential intervention effect estimates

	Model for the naïve estimate	Model for the corrected estimate
Individual factors		
Age (vs. 35–49)		
50–64	+0.02 –0.08, +0.12	+0.02 –0.06, +0.09
65 and over	–0.02 –0.16, +0.13	–0.02 –0.12, +0.09
Male (vs. female)	–0.03 –0.11, +0.05	–0.02 –0.08, +0.04
Living alone (vs. as a couple)	–0.02 –0.11, +0.07	–0.05 –0.11, +0.02
Education (vs. ≤ low secondary)		
Upper secondary, low tertiary	–0.02 –0.12, +0.07	–0.02 –0.09, +0.05
Intermediate tertiary	+0.09 –0.03, +0.21	+0.04 –0.05, +0.12
Upper tertiary	–0.07 –0.17, +0.03	–0.06 –0.13, +0.02
Employment status (vs. stable job)		
Precarious job	–0.07 –0.27, +0.14	–0.02 –0.18, +0.13
Unemployment	+0.16 –0.09, +0.41	+0.14 –0.04, +0.33
Household income per consumption unit (vs. ≤1285 €)		
>1285 – ≤2200 €	+0.00 –0.08, +0.09	+0.01 –0.06, +0.08
>2200 €	–0.02 –0.11, +0.08	+0.00 –0.07, +0.07
Services as a neighborhood selection factor (vs. low)		
Intermediate	+0.05 –0.07, +0.15	+0.06 –0.02, +0.14
High	+0.05 –0.06, +0.16	+0.06 –0.03, +0.14
Public transport as a neighborhood selection factor (vs. low)		
Intermediate	–0.03 –0.15, +0.10	–0.01 –0.10, +0.08
High	–0.01, –0.11, +0.09	–0.02 –0.10, +0.06
Bike used in previous trips from home	–	–0.51 –0.59, –0.44
Personal vehicle used in previous trips from home (vs. no)		
In some of the trips	–	–0.32 –0.37, –0.27
In all trips	–	–0.56 –0.60, –0.53
Environmental factors		
Number of services, residential neighborhood		
Linear term	+0.21 +0.11, +0.32	+0.02 –0.07, +0.10
Quadratic term	–0.04 –0.07, –0.01	–0.01 –0.03, +0.02
Number of services, trip origin		
Linear term	–	+0.03 –0.02, +0.08
Quadratic term	–	–0.01 –0.02, +0.00
Number of services, trip destination		
Linear term	–	+0.10 +0.05, +0.15
Quadratic term	–	–0.01 –0.02, –0.00

eAppendix 5: A posteriori recalculation of the naïve biased residential intervention effect estimate

Methodology

To reach an analytical understanding of the genesis of the bias, we recalculated the naïve estimate of the intervention effect from a model accounting for the trip-level number of services. In our naïve model, influences on walking of the nonresidential places visited are spuriously incorporated in the residential neighborhood-walking association when the number of services at these visited places is similar to the residential number of services. Our aim was to mimic this process.

To do so, we had to determine whether the number of services in each nonresidential place visited was "similar" or not to the residential number of services. For the nonresidential place of a participant X, we constructed a database comprising this nonresidential place of X and all the nonresidential places of the other participants. For each of these nonresidential places in the database, we calculated the absolute value of the difference between the nonresidential number of services and the residential number of services of participant X. The number of services in the participant X's nonresidential place buffer was considered to be similar to participant X's residential number of services if the corresponding difference was below the first decile, the second decile, the third decile, the fourth decile, or the fifth decile of ranked differences (alternative definitions of "similarity").

In our recalculation of the naïve estimate, the number of services in a nonresidential place (even if not overlapping the residential neighborhood) was spuriously raised to the intervention target (200, 500, or 1000) if this nonresidential place was "similar" to the residential neighborhood in terms of services.

To recalculate the naïve intervention effect estimate, we re-estimated the regression model for walking with sociodemographic variables, neighborhood selection factors, and the residential, trip origin, and trip destination numbers of services as explanatory variables but without modes used in previous trips (as nonresidential effects incorporated in the naïve estimate are confounded by these modes in previous trips). Based on model coefficients, we calculated the predicted probability of entirely walking in each trip from all model covariates (including the residential, trip origin, and trip destination numbers of services, modified as explained above). This calculation was performed for the pre-intervention state and for each of the post-intervention scenarios (residential services raised to 200, 500, or 1000). For each of these four cases, we calculated the average probability of walking in a trip across all individuals and trips. The intervention effect estimate was computed for each intervention level, and for each cutoff to define whether a nonresidential place was similar to the residential neighborhood in terms of services, as the post-intervention average probability of walking minus the pre-intervention probability, only among participants who experimented the hypothetical intervention (i.e., with less than 200, 500, or 1000 services in their residential neighborhood).

Results

The model that was estimated is reported in eAppendix Table 2. When no adjustment was made for the modes in previous trips, both the trip origin and trip destination numbers of services were positively associated with the probability that a trip is walked (with quadratic effects).

The recalculation of the naïve biased estimate implied to spuriously integrate in the residential neighborhood-walking association the influence on walking of the nonresidential places visited if their number of services was "similar" to the residential number of services.

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eAppendix Table 3 reports such recalculated naïve estimates for a low threshold (1st decile) to define such similarity (corresponding to a low level of bias) to a higher threshold (5th decile) to define such similarity (corresponding to a higher level of bias). The recalculated estimate was most comparable to the naïve estimate when the effect of nonresidential places was spuriously integrated in the residential neighborhood-walking association if the difference in services between the residential and nonresidential places was below the third or fourth decile of differences for all participants.

eAppendix Table 2. Regression model estimated to determine the recalculated residential intervention effect estimate

Individual factors		
Age (vs. 35–49)		
50–64	+0.03	–0.07, +0.13
65 and over	–0.01	–0.15, +0.13
Male (vs. female)	–0.03	–0.11, +0.05
Living alone (vs. as a couple)	–0.03	–0.11, +0.06
Education (vs. ≤ low secondary)		
Upper secondary, low tertiary	–0.03	–0.12, +0.06
Intermediate tertiary	+0.07	–0.04, +0.19
Upper tertiary	–0.07	–0.17, +0.02
Employment status (vs. stable job)		
Precarious job	–0.06	–0.27, +0.14
Unemployment	+0.20	–0.05, +0.44
Household income per consumption unit (vs. ≤1285 €)		
>1285 – ≤2200 €	+0.00	–0.09, +0.09
>2200 €	–0.01	–0.11, +0.08
Services as a neighborhood selection factor (vs. low)		
Intermediate	+0.03	–0.08, +0.14
High	+0.04	–0.07, +0.15
Public transport as a neighborhood selection factor (vs. low)		
Intermediate	–0.03	–0.15, +0.09
High	–0.02	–0.12, +0.08
Environmental factors		
Number of services, residential neighborhood		
Linear term	+0.04	–0.07, +0.15
Quadratic term	–0.01	–0.04, +0.02

Number of services, trip origin			
Linear term		+0.10	+0.05, +0.16
Quadratic term		–0.02	–0.03, –0.01
Number of services, trip destination			
Linear term		+0.12	+0.07, +0.17
Quadratic term		–0.02	–0.03, –0.01

eAppendix Table 3. Recalculation* of the naïve estimate of the hypothetical intervention effect of raising the number of services in the residential neighborhood to 200, 500, or 1000 for participants in the intervention groups (i.e., with a residential number of services below 200, 500, or 1000), according to the degree of similarity between the nonresidential and residential places needed to spuriously transfer the effect†

Transfer of nonresidential effect to the residential association if the two places are similar	Intervention: residential number of services raised to 200	Intervention: residential number of services raised to 500	Intervention: residential number of services raised to 1000
Similar if below the 1st decile†	0.016 (0.007, 0.025)	0.044 (0.020, 0.069)	0.089 (0.043, 0.135)
Similar if below the 2nd decile†	0.017 (0.008, 0.027)	0.050 (0.025, 0.074)	0.099 (0.054, 0.145)
Similar if below the 3rd decile†	0.018 (0.009, 0.027)	0.053 (0.029, 0.078)	0.107 (0.062, 0.153)
Similar if below the 4th decile†	0.018 (0.009, 0.028)	0.056 (0.031, 0.081)	0.114 (0.068, 0.159)
Similar if below the 5th decile†	0.018 (0.009, 0.028)	0.057 (0.032, 0.082)	0.117 (0.071, 0.162)

* The exact set of predictors included in the model to recalculate the naïve estimate is reported in eAppendix Table 2. The intervention effect estimate is expressed on the probability scale.

† In the recalculation of the naïve estimate, the number of services in a nonresidential place was spuriously raised to 200, 500, or 1000 if the difference in the number of services between the nonresidential place and the residential neighborhood was below the 1st decile, 2nd decile, 3rd decile, 4th decile, and 5th decile of the differences in the number of services between nonresidential and residential places for all participants.

eAppendix 6: Advanced interpretation of the "residential" effect fallacy bias

Several aspects warrant additional comments.

Source of the correlation between exposures at the residential and nonresidential places visited

The correlation between exposures at the residential and nonresidential places visited may be attributable to a large extent to the spatial autocorrelation in the density of services, but also among other mechanisms to the fact that the residential environment determines mode choice and that mode choice influences which nonresidential environments are visited during daily activities (public transport bringing people from high density to high density areas, and car allowing to travel from remote areas to remote areas). The influence of the latter mechanism on the probability of walking in the nonresidential places visited was captured by the residential association in the naïve model, but was picked up by the trip origin / destination associations in the corrected model and therefore removed from the intervention effect estimate. This is a desirable consequence of our correction because a residential intervention would likely not change the modes used in the nonresidential environments visited far from the residence.

Overall behavioral outcome vs. residential neighborhood-specific behavioral outcome

The "residential" effect fallacy described in this article applies to studies correlating residential environment characteristics with overall behavioral outcomes (cumulating behavior conducted inside and outside the residential neighborhood). This bias would not apply to the few studies that investigated associations between residential characteristics and a location-specific outcome (e.g., behavior only in the residential neighborhood).[8,10-12]

However, it should be noted that studies that only consider a location-specific behavioral outcome are of limited interest, since what matters in a Public health perspective is not where people practice a behavior but whether their overall behavior is concordant with health recommendations. Thus relying on an outcome only for the portion of the behavior that takes place in the residential neighborhood neither implies an awareness of the "residential" effect fallacy nor is a proper way to solve it.

Can the "residential" effect fallacy lead to an underestimation of residential effects?

It is indicated in this article that the "residential" effect fallacy leads to an overestimation of the effect of residential characteristics. This is attributable to the fact that environmental characteristics in residential and nonresidential places are positively correlated. It is difficult to think to a case where a residential characteristic would be negatively correlated with the corresponding characteristic in nonresidential environments. However, if that were happening, the "residential" effect fallacy bias would lead to an underestimation of the residential environment effect.

Interferences between participants

We took into account the extent to which an intervention in the residential neighborhood of participant P1 influenced the nonresidential neighborhoods of participant P1, but our calculations made the assumption that interventions in the residential neighborhoods of participants P2, P3, P4, etc. could not influence the nonresidential neighborhoods of participant P1, even if there was some overlap between them. Thus, the present study was based on the assumption that a nonresidential neighborhood of participant P1 could be affected by the intervention only if this nonresidential neighborhood overlapped the residential neighborhood of participant P1, but not by overlapping the residential

neighborhood of other participants (P2, P3, P4, etc.). This assumption would be violated if a significant fraction of each participant's nonresidential neighborhoods overlapped the residential neighborhoods of other participants where the intervention was implemented. Our first motivation to follow this approach ignoring interferences between participants was that, typically, an intervention to raise the number of services would not be conducted in all places lacking services over an entire region or country, but in very definite neighborhoods to target some of the populations with the greatest needs. Thus, in case of an intervention to develop services, it is relatively unlikely for a participant affected by the intervention in her/his residential neighborhood to be also affected in some of her/his nonresidential places located relatively far from the residence. Our second motivation to not take into account these interferences between participants is that the induced effect would vary from one study to the other, according to the number of intervention areas disseminated over the study territory and size of this territory, but also according to the patterns of mobility of participants.

Despite this theoretical preference for an intervention effect estimate that does not take into account interferences, we have recalculated the intervention effect estimate taking into account these interferences, as a sensitivity analysis. When interferences between participants were disregarded, the percentage of nonresidential buffers visited by a participant X that overlapped the residential area of the same participant X had a median value of 41.1% across the participants (interquartile range: 20.0%, 61.9%). As a comparison, when interferences between participants were taken into account, the percentage of nonresidential buffers visited by a participant X that overlapped the residential area of any participant had a median value of 88.9 (interquartile range: 71.9%, 96.3%). Thus, even with only 227 participants spread over a large study territory, accounting for interferences between individuals had a substantial impact on the percentage of nonresidential buffers that were affected by the intervention (due

to the large 1 km radius selected for the residential intervention areas and nonresidential areas).

We report in eAppendix Table 4 the information already provided in Table 2 in the main article. We have added to this Table the estimate of the intervention effect corrected from the "residential" effect fallacy and taking into account the interferences between the participants.

eAppendix Table 4. Naïve and corrected estimates of the hypothetical intervention effect of raising the number of services in the residential neighborhood to 200, 500, or 1000 for participants in the intervention groups (i.e., with a residential number of services below 200, 500, or 1000)[a]

	Intervention: residential number of services raised to 200	Intervention: residential number of services raised to 500	Intervention: residential number of services raised to 1000
Naïve estimate	0.020 (0.010, 0.029)	0.055 (0.030, 0.079)	0.109 (0.063, 0.154)
Corrected estimate	0.007 (0.001, 0.014)	0.019 (0.000, 0.038)	0.039 (0.004, 0.073)
Corrected estimates taking into account interferences	0.007 (0.000, 0.014)	0.021 (0.003, 0.040)	0.045 (0.010, 0.079)

[a]The exact sets of predictors included in the naïve estimate model and in the corrected estimate models are reported in Supplementary Table 1. The intervention effect estimate is expressed on the probability scale.

There was no difference between the two corrected estimates – without and with the interferences between participants – for the intervention raising the number of services to 200, while differences appeared for the intervention raising the number of services to 500, and became larger for the one raising them to 1000. As expected, the intervention effect estimate became higher when taking into account the interferences between participants. However, this increase in the size of the corrected effect estimate when taking into account the interferences between participants was of much lower magnitude than the "residential" effect fallacy itself.

This novel estimate is provided for quantifying interferences between participants but it is not more valid than our corrected estimate that does not account for interferences. This estimate is related to a different intervention where not only the residential neighborhood but also other portions of the activity space of the participants would receive the intervention,

which is different than our original estimation target. Whereas the intervention of interest in this article has a univocal definition (affecting a given area around the residence), the estimate accounting for interferences relates to an intervention with an equivocal definition, as it depends on the magnitude of these interferences.

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