Published in final edited form as:

J Expo Sci Environ Epidemiol. 2020 March ; 30(2): 299–308. doi:10.1038/s41370-019-0167-9.

Characterizing community-wide housing attributes using georeferenced street-level photography

Zoe E. Petropoulos, B.S.^a, Jonathan I. Levy, Sc.D.^a, Madeleine K. Scammell, D. Sc.^a, M. Patricia Fabian, Sc.D.^a

^aDepartment of Environmental Health, Boston University School of Public Health, 715 Albany Street, Boston, MA 02118 USA

Abstract

New methods are needed to efficiently characterize built environment attributes and residential behaviors to improve exposure assessment in epidemiologic research, given limitations of available databases and approaches. Window opening and presence of air conditioning (AC) units predict indoor air quality and thermal comfort, but data are not widely available. In this study, we tested the utility of a GIS-based tool for rapidly assessing open windows and window/wall air conditioning units in the city of Chelsea, Massachusetts using georeferenced street-level photographs and crowdsourced online surveys. We characterized open windows and window/wall AC units for 969 parcels in the winter and 1 213 parcels in the summer, requiring approximately 40 person-hours per season. In the winter, 21% of parcels surveyed had a window or wall AC unit and 19% had an open window. In the summer, 69% had a window or wall AC unit and 53% had an open window. We demonstrated an efficient method for rapidly characterizing open windows and window/wall AC units across an entire city. This tool can help characterize exposures for epidemiological research, engage community members, and inform local land use planning and decision-making.

Keywords

Exposure assessment; residential behavior; neighborhood; photo survey; window opening; geographic information system

Introduction

There is a growing body of evidence demonstrating that characteristics of an individual's housing and neighborhood environments are strongly associated with health outcomes. For example, researchers have found that the greening of vacant lots is associated with decreased rates of depression and self-reported poor mental health for residents living near those lots.

Users may view, print, copy, and download text and data-mine the content in such documents, for the purposes of academic research, subject always to the full Conditions of use:http://www.nature.com/authors/editorial_policies/license.html#terms

Corresponding Author Contact Information: Zoe Petropoulos, Address: 715 Albany Street, 427W, Boston, MA 02118 USA, zep@bu.edu, Telephone: 617-358-2724, Fax: 617-358-2642.

Declarations of Interest: None

Conflicts of Interest: The authors declare no competing financial interests in relation to this work.

(1) Other research has demonstrated a relationship between obesity and neighborhood walkability, accessibility to green space and parks, and perceived neighborhood safety.(2,3) Inside the home, researchers have found that housing type and condition and indoor air quality are associated with adverse respiratory outcomes among children.(4,5)

Previous efforts to characterize the built environment have included the use of satellite data, field observations and audits, and questionnaires, but none of these methods allow for efficient collection of high-resolution and high-quality data over broad spatial scales. Satellite imagery has been used to estimate residential exposure to greenness,(6) exposure to blue spaces,(7) quality of open spaces,(8) and the extent and greenness of pedestrian trails. (9) In spite of their efficiency and broad coverage, satellite-derived products may not provide detailed enough information for accurately assigning exposures at smaller geographic scales. In contrast, field observations can be used to collect objective measures of characteristics and behaviors on a smaller spatial scale with greater detail, such as the quality of the walking and biking environment (10-12) and window opening behavior.(13) However, conducting field surveys to monitor residential behavior is resource- and time-intensive, and may only capture certain parameters across a brief period or a limited geography.(13) Questionnaires of population sub-samples are commonly used to collect a wide variety of information about housing and neighborhood characteristics and residential behaviors, particularly among participants of epidemiological studies. One key advantage is the ability to ask about subjective measures, like perceived neighborhood safety (14-16) and perceived noise levels,(17,18) or behaviors, like methods of indoor temperature control.(19,20) However, these types of questionnaires are labor-intensive and can suffer from issues of accuracy and generalizability. Mail-in and phone surveys may be at-risk of low participation rates, (20,21) which can produce biased results or limit the generalizability.(22)

One strategy to enhance high-resolution data on the built environment is to use street-level imagery to assess certain neighborhood characteristics remotely, with greater ease and efficiency.(23,24) Especially with targeted data collection that goes beyond public databases or resources, a large amount of neighborhood-level information can be collected without surveys or other resident participation. This includes infrastructure conditions (dilapidated housing, damage to public infrastructure, graffiti, etc.), neighborhood characteristics (trees, sidewalks, retail area, parks, etc.), and even residential behaviors (trash and recycling bin use, window-opening, use of air conditioning units, etc.). While this strategy for data capture requires significant image processing capabilities, a variety of methods have recently become available to quickly process large numbers of images into useable data. For example, computer scientists at the University of Maryland have designed a method that combines machine learning and Amazon Mechanical Turk, a crowdsourcing platform, to rapidly identify the presence or absence of curb ramps using Google Street View images from various cities.(25)

One category of residential behaviors for which these novel strategies would be beneficial are window opening and air conditioning (AC) use. These residential behaviors modify exposure to harmful air pollutants and heat in the indoor environment.(26-28) AC in the home (specifically central AC) is associated with mortality reductions, including during large-scale heat wave events.(29-32) In spite of their importance, these two attributes are not

commonly available from public databases, and no protocols exist to characterize window opening and AC unit presence across a neighborhood or city.

In this study, we applied a novel method of capturing housing information across an entire city using georeferenced street-level photographs and a crowdsourced image processing strategy. We focused on characterizing the presence of window or wall AC units and open windows, while developing data capture strategies that would generalize to other built environment attributes. This work was conducted as part of the Center for Research on Environmental and Social Stressors in Housing Across the Life Course (CRESSH), one of the five Centers of Excellence on Environmental Health Disparities (EHD) Research programs.

Methods

Overview & location.

Our objectives were to: 1) test the utility of street-level photography and crowdsourced surveys for characterizing building attributes across an entire city and 2) capture the seasonal window opening behavior and AC unit presence for residential properties in the city of Chelsea, Massachusetts. Chelsea is a city located immediately northeast of Boston with a population of approximately 40 000 in an area of 5.7 square kilometers, making it one of the most densely populated cities in Massachusetts.(33) The Chelsea population is predominately of Hispanic or Latino origin (65.6%) and 69.9% speak a language other than English at home.(34) Chelsea is one of two partner cities of CRESSH and is considered an environmental justice community because of the proportion of minority and lower income residents.(35) Examining presence of AC units in this city is important because residents may be disproportionately affected by extreme heat events. Previous research has demonstrated that race, poverty, and homeownership are strong predictors of AC ownership. (30,36,37)

Street-level photography overview.

We used ArcGIS Photo Survey (Esri, Redlands, CA), which allows users to link georeferenced photographs to a reference file, such as a shapefile of parcels, using ArcGIS Pro (Version 1.4 or later, Esri). Photos are matched to parcels using an algorithm based on distance and orientation of the camera. Once linked to parcels, ArcGIS Online (Esri) is used to add customizable survey questions to the photographs, which can be published online. The surveys can then be completed by anyone who has the link and access to the webpage, facilitating sharing with a broader audience and the ability to crowdsource the responses.

Community organization engagement.

Through CRESSH community partners, researchers engaged with the local beautification committee and staff of the Department of Public Works in Chelsea. In these meetings, we described the photo survey, obtained feedback on its implementation, and brainstormed how the photo survey could potentially inform community-oriented programs or policies.

Photograph collection.

We collected photos on one day in February 2017 and one day in July 2017 in order to capture winter/summer seasonal variability in resident behavior. Driving directions were created using an online route creation tool (e.g. Google Maps) to optimize the route to capture the maximum number of Chelsea residences. Resources needed included a vehicle, two cameras with built-in GPS (VIRB® XE, Garmin, Olathe, KS), and camera mounts (RAM-B-166-GOP1, RAM Mounts, Seattle, WA). Cameras were installed at the top of the partially rolled-down vehicle windows on the back windows of both the driver and passenger sides (Figure 1). Optimal camera angle adjustment was determined after conducting a pilot survey. Optimal camera angle will depend on vehicle height, road width, and average building height. The two cameras, set to take bursts of 30 photos in 6 seconds for every click, were controlled manually using the free VIRB mobile app (Garmin), which allowed for pauses in photo capture at traffic lights and other stops. Three people were needed to drive, direct to the optimal route, operate the cameras, and take notes.

Photograph cleaning.

Before uploading the photos into ArcGIS Pro using the Photo Survey toolbox, we deleted unnecessary or unusable photos. These included duplicates (e.g. result of being stopped at an intersection while cameras were in use), photos of anything except residences (e.g. parking lots, parks), and photos that included faces of individuals. We restricted the number of photos attached to each parcel to 11 or fewer for most buildings, as a greater number of photos impaired the user interface of the resulting surveys.

Survey creation.

Software used to link the survey to the photos and to publish the surveys included ArcGIS Pro (Versions 1.4 and 2.0, Esri), an ArcGIS Online account with publishing permissions (Esri), the Photo Survey toolbox (June 2016 Version, Esri), and Microsoft Internet Information Services (IIS) (Microsoft Corporation, Redmond, WA). The instructions for creating a survey using the Photo Survey tool can be found on the Esri website.⁽³⁸⁾ Briefly, photos are uploaded into ArcGIS Pro using the Photo Survey toolbox and joined to the respective parcels in a parcel shapefile. The resulting feature layer is shared to an ArcGIS Online account, where survey questions are added as a customizable pop-up window in a new web map. The web map is published to a web server using IIS, and the resulting link is shareable to the desired audience. The parcel shapefile for Chelsea was obtained through the MassGIS Online Portal (Massachusetts Bureau of Geographic Information, 2017).

Survey question development.

Based in part on our conversations with community partners, we created an initial list of eighteen candidate questions. The topics for survey questions proposed by community members ranged from recycling bin use and overflowing trash bins to sidewalk tree plots, overgrown vegetation, litter, and graffiti. Meetings and email correspondence were used to determine what questions would obtain useful and actionable data for the community. Questions relating to trash cans and recycling bins were removed because those objects were not explicitly captured in all of the pilot survey photos due to the day of week or time of day

photos were captured or because the scenario in the question (e.g. overflowing trash cans) was not common. Similarly, sidewalk tree plots were frequently covered by snow or blocked from view by parked cars. Litter, graffiti, and blighted homes were rare in the photographs collected, so we removed the questions pertaining to these items. We ultimately reduced the number of questions to the three that were most central to CRESSH project aims and could most accurately and rapidly be characterized using our photos: 1) How many stories tall is this building?, 2) Do you see any open windows and if so, what floor are they on?, and 3) Do you see any window air conditioning units or wall air conditioning units on the building?

Survey crowdsourcing.

The survey link was hosted on the CRESSH website (www.cressh.org) and shared via the CRESSH electronic mailing list and Twitter account. The link was also shared directly to the research community by email and word-of-mouth. Survey takers could either complete surveys as anonymous guests or sign into their personal Twitter account. Figure 2 shows an example of a survey. As volunteers scanned photos and answered surveys, data from their responses were stored in the hosted feature layer in ArcGIS Online used to make the surveys. In ArcGIS Online, these data could be viewed by the research team as an interactive table and used to generate summary statistics. Survey takers could skip questions, select from the group of associated photographs which was the best angle shot, and add comments to each survey. If a survey was skipped, the associated photographs & survey questions were returned to the queue for another survey taker to complete.

Pilot surveys.

Two pilot surveys were conducted. The first was conducted on two streets in the South End neighborhood of Boston near Boston Medical Center. This pilot was conducted to evaluate the accuracy of the parcel matching feature of the Photo Survey toolbox and to compare two photograph collection methods—walking and driving. The second pilot survey, conducted in Chelsea, was used to determine the optimal survey questions, camera placement, and consistency of photo survey answers between survey takers.

From our pilot studies, we found that photographs collected while driving were equally useable as those collected while walking, with the added benefit of increased efficiency. The pilot survey results also indicated that the Photo Survey algorithm to assign photos to parcels was accurate enough for our purposes (i.e. in a test using 90 photographs, only 3 parcels of 29 had photographs that were incorrectly assigned in a neighborhood with narrow parcels). The second pilot survey revealed that, for a few of the residences, the entire face of the building was not captured in the photograph, which was common for tall apartment buildings close to the street. This resulted in camera positioning adjustments lower on the vehicle windows and tilted slightly upwards. To test the consistency of survey answers during the second pilot survey, we had two members of the research team take the same ten surveys and compare answers. We found that answers about the number of stories and the presence of AC units were very consistent, whereas answers about open windows sometimes differed. This was likely due to reflections off of windows and open blinds sometimes obscuring the ability to discern whether a window was open or not. To minimize misclassification, we created guidelines with sample snapshots of open and closed windows

which we included on the webpage where survey takers were navigated when clicking on our link.

Linkages to public databases.

To test whether the survey answers could be easily linked to external housing- and neighborhood-specific data, we linked both the winter and summer survey results to various public databases using parcel identification numbers. These included parcel data from the 2016 Chelsea Assessor's Database (39) and sociodemographic data from the American Community Survey (ACS) 2010-2014 5-Year Estimates. These datasets were merged with the photo survey results using SAS 9.4 (SAS Institute, Cary, NC). SAS 9.4 was also used to generate descriptive statistics and tables.

Results

After removing surveys with incomplete answers (in which cars or trees blocked the face of the building, for example), the surveys captured 969 parcels in the winter and 1 213 parcels in the summer, out of an estimated 3 494 residential parcels in Chelsea. To estimate the percentage of residential parcels captured on just the streets we drove down, we calculated the number of surveyed parcels and total parcels for 21 of the street segments that were captured during the winter survey. The average percentage of residential parcels captured in the survey for those street segments was 69.7%, with a range of 38.7%–100%.

Summary statistics for the parcels captured in the winter and summer are listed in Table 1. We captured 25.2% more parcels in the summer due to an improved driving route. The winter route captured a higher percentage of single family homes while the summer route captured more condominiums. Sociodemographic characteristics of the captured parcels were comparable in both seasons. Data used from the ACS are mean values for block group and the parcels were assigned the mean value for the respective block group. We averaged these variables at the parcel level, but it should be noted that sociodemographic information at the parcel-level was unavailable. Weather conditions on the day of photograph collection and the results of the surveys are reported in Table 2. As expected, open windows and AC units were more common in the summer than in the winter; however, even in the winter 20.9% of residences surveyed had a window or wall AC unit, with window ACs predominantly in single family and multi-family homes. In the winter, the most common occurrence for open windows was the top floor alone. In the summer, open windows were slightly more common on floors other than the top. Almost 40% of the residences surveyed in the summer had both an open window and an AC unit; however, this number includes multi-unit buildings so open windows and AC units did not necessarily belong to the same unit in these cases, and the presence of an AC unit does not indicate its use during the photo survey. A break-down of the housing types with both open windows and AC units shows that apartment buildings and stores or shops were more likely to have both open windows and AC units than other housing types. Some parcels that are categorized as stores or shops in the Chelsea Assessors Database were included in our photo surveys because multi-story buildings of this type often included apartment units on upper floors. Not listed here are percentages for parcels of other non-residential types (e.g. churches, public administrative

offices) as these were not captured in the surveys. Of the residential parcels of Chelsea, the surveys appear to have captured a broad spatial distribution (Figures 3 and 4).

Discussion

We demonstrated an efficient method for capturing housing attributes and residential behaviors representative of an entire community that can be replicated for other housing or neighborhood characteristics of interest to researchers, community members, or local governments. With a team of three researchers in one vehicle with two cameras, the total time required to drive the constructed route and photograph the residential parcels was approximately four hours on each day. There were approximately 14 000 photos (40 gigabytes) collected for each of the two surveys. Deleting duplicate photos and those that were not of houses required 12-14 hours. Post processing, there were approximately 5 000 residential photos (14 gigabytes) per season. Setting up the photo survey in ArcGIS Pro and ArcGIS Online required approximately five hours. At an estimated 30 seconds per survey, survey completion only required 8.8 person hours for the winter survey and 12.2 person hours for the summer survey. Overall, the estimated time to complete data collection in the winter and summer—which included collecting, processing, and classifying the photos—was 40 person hours and 43 person hours, respectively. More time was required in the summer because of a greater number of surveys. In total, we were able to characterize multiple attributes of numerous housing parcels at approximately 2-2.5 minutes per parcel.

By comparison, other approaches used to capture window opening behavior and AC presence have not been able to achieve the same degree of coverage with the same investment of resources. Johnson and Long used visual surveys conducted by field technicians to observe open windows at 1 100 residences in 48 census tracts in Durham, North Carolina across a period of 1.5 years.(13) The visual surveys were divided into 72 2-hour sessions, totaling 144 hours of field work. The number of residences included in this study is comparable to the number captured in our photo surveys, however, the Photo Survey tool allowed this data to be captured with less than half of the amount of person-time and a much more rapid completion of field data collection. A study using magnetic strips to monitor window opening in Beijing and Nanjing, China captured data for 8 apartments across one year, with approximately 20 days of monitoring per season.(40) While this approach allows for greater detail regarding time of day and duration, the researchers were limited by the number of residences they could monitor, limiting the ability to determine sociodemographic or household predictors of window opening. Another study surveying residents about their window-opening behavior examined predictors of window-opening in Danish households.(20) Response rates were 19% for the initial survey, and 75% for the follow-up surveys (conducted only among those who completed the initial survey). While this data collection method is presumed to require less time and effort by the researchers, the resulting data may be biased by the types of participants who responded and may not represent the entire population they attempted to describe.

The ability to link the geotagged photos to publicly available datasets allows us to expand the characterization of housing attributes in many dimensions. In this case, we linked the photos to housing and sociodemographic information, which can be used to determine

whether there are factors that strongly predict resident behaviors. Photographs can be used in subsequent surveys for different purposes if new research questions arise, and the results can be linked to databases specific to community organization interests (e.g. beautification, infrastructure, arbor committees). Use of either crowdsourcing, image processing software, or machine learning algorithms can provide rapid and accurate insights on the built environment throughout a city.

Our findings indicate that almost one fifth of households surveyed in the winter had at least one open window, half of which were reported to be only on the top floor. Overheating has been documented as an issue for units on the top floors of multi-story buildings.(41) Crime prevention and privacy may also motivate closing of windows on bottom floors (42) because of the use of windows as an entry point for burglars,(43) however, more research is needed to understand why so many households in Chelsea had open windows in the winter and why there were differences by floor. We also found that many parcels, especially in the summer (38.3%), had both an open window and an AC unit. However, this does not imply that the AC units are in use while windows are open. Surveys of residents are needed to better understand when AC units are in use.

There are some limitations to using street-level photography and crowdsourced surveys to collect information on household or neighborhood characteristics. A GPS-enabled camera and GIS software are both required, which may be cost-prohibitive for some wishing to employ this method. More specific limitations include the potential for obstacles, such as trees and cars, which may block view of houses or features of interest in the photographs. Photographs may also only reflect the portions of houses or other features that face the road, which may limit the types of survey questions or the accuracy of survey answers. This applied to our photo surveys for both open windows and AC units. We were also unable to capture central AC ownership in our survey for the same reason. A field survey could be concurrently conducted for a subset of parcels during photograph collection to verify open windows and determine whether other sides of residential buildings differ from the side facing the street. Researchers interested in building predictive models of these residential behaviors should incorporate weather-related variables into their models, as weather conditions (precipitation, temperature, wind speed, etc.) are likely important predictors of these behaviors.

While our community partners provided a number of ways that the photo surveys could capture data that would be useful to them, most of these were unfortunately impractical in these initial surveys. The recycling and trash in Chelsea is collected on different days depending on the given street, so capturing recycling and trash bin behaviors for the whole city would have been impossible with the photos collected on one day in each season. This could be addressed by mounting cameras to vehicles with regular routes, such as trash collection vehicles, to make photograph collection more efficient; however, this was not possible with limited time and resources. Another community need was a map of empty tree plots across the city to inform tree-planting efforts. Unfortunately, we found that most sidewalk tree plots were blocked by cars in both seasons and snow in the winter. Others using the photo survey may also find that sidewalk-area attributes are hard to capture for this reason. Finally, the community partners were interested in a map of methane-damaged trees

throughout the city, which can indicate leaking methane gas lines. Even though many of the summer survey photos captured trees, a question about methane damage would have required trained survey-takers, which was not possible given the crowdsourced approach.

Despite these limitations, researchers, community organizations, and local governments may find this approach to be simple and versatile enough for them to employ to capture residential behaviors and built environment characteristics. This approach to data collection can be used to concurrently capture information relevant to researchers and community stakeholders—which may include data on blighted or damaged homes, litter, overgrown vegetation, and graffiti. Epidemiologists can link parcel-level variables like open windows and AC unit ownership to heat- and air pollution-related health outcome data to capture these potential exposure modifiers in their research. This photo survey approach also allows for the engagement of community members in the photograph collection, survey design, and classification of photographs. Engaging community members in survey completion also allows for the inclusion of questions related to the perception of environmental quality. This tool can be employed to build predictive models of window-opening behaviors and AC unit ownership across entire communities, which can inform our understanding of disparities in exposures to indoor air pollutants and temperature extremes.

Acknowledgments / Funding Sources:

This work was supported by the National Institute of Environmental Health Sciences (grant number T32 ES014562), the National Institute on Minority Health and Health Disparities (grant number P50 MD010428), and the U.S. Environmental Protection Agency (grant number RD-836156). The funding sources had no involvement in the conduct of this research or preparation of this manuscript. There were no other sources of financial support, sponsorship, or materials.

The authors thank GreenRoots, the Chelsea Beautification Committee, and the Chelsea Department of Public Works for their input and ideas related to applications of this data collection method. Additionally, we would like to acknowledge Raquel Jimenez Celsi, Daniel Nguyen, Leila Heidari, Felipe Jordan Colzani, Iman Ali, Bailey Alvarado, and Baderha Bujiriri for their important contributions to photograph collection and survey testing. Finally, we wish to thank Chris Buscaglia for his help in setting up the surveys and everyone who completed the surveys online.

Bibliography

1. South EC, Hohl BC, Kondo MC, MacDonald JM, Branas CC. Effect of Greening Vacant Land on Mental Health of Community-Dwelling Adults. *JAMA Netw Open* [Internet]. 2018 7 20 [cited 2018 Sep 8];1(3):e180298 Available from: <http://jamanetworkopen.jamanetwork.com/article.aspx?doi=10.1001/jamanetworkopen.2018.0298> [PubMed: 30646029]
2. Wall MM, Larson NI, Forsyth A, Van Riper DC, Graham DJ, Story MT, et al. Patterns of Obesogenic Neighborhood Features and Adolescent Weight: A Comparison of Statistical Approaches. *Am J Prev Med* [Internet]. 2012 5 1 [cited 2018 Apr 4];42(5):e65–75. Available from: <https://www.sciencedirect.com/science/article/pii/S0749379712001316> [PubMed: 22516505]
3. Sallis JF, Glanz K. Physical Activity and Food Environments: Solutions to the Obesity Epidemic. *Milbank Q* [Internet]. 2009 3 1 [cited 2018 Apr 4];87(1):123–54. Available from: <http://doi.wiley.com/10.1111/j.1468-0009.2009.00550.x> [PubMed: 19298418]
4. Emenius G, Svartengren M, Korstaad J, Nordvall L, Pershagen G, Wickman M. Building characteristics, indoor air quality and recurrent wheezing in very young children (BAMSE). *Indoor Air* [Internet]. 2004 2 1 [cited 2018 Sep 7];14(1):34–42. Available from: <http://doi.wiley.Com/10.1046/j.1600-0668.2003.00207.x> [PubMed: 14756844]
5. Bailie R, Stevens M, McDonald E, Brewster D, Guthridge S. Exploring cross-sectional associations between common childhood illness, housing and social conditions in remote Australian Aboriginal

- communities. BMC Public Health [Internet]. 2010 12 20 [cited 2018 Sep 7];10(1):147 Available from: <http://bmcpublichealth.biomedcentral.com/articles/10.1186/1471-2458-10-147> [PubMed: 20302661]
6. Almanza E, Jerrett M, Dunton G, Seto E, Pentz MA. A study of community design, greenness, and physical activity in children using satellite, GPS and accelerometer data. Health Place [Internet]. 2012;18(1):46–54. Available from: <http://www.sciencedirect.com/science/article/pii/S135382921100164X> [PubMed: 22243906]
 7. Gascon M, Sánchez-Benavides G, Dadvand P, Martínez D, Gramunt N, Gotsens X, et al. Long-term exposure to residential green and blue spaces and anxiety and depression in adults: A cross-sectional study. Environ Res [Internet]. 2018 4 [cited 2018 Apr 4];162:231–9. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0013935118300124> [PubMed: 29358115]
 8. Taylor BT, Fernando P, Bauman AE, Williamson A, Craig JC, Redman S. Measuring the Quality of Public Open Space Using Google Earth. Am J Prev Med [Internet]. 2011 2 1 [cited 2018 May 27];40(2):105–12. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0749379710006343> [PubMed: 21238857]
 9. Wilson J, Lindsey G, Liu G. Viewshed characteristics of urban pedestrian trails, Indianapolis, Indiana, USA. J Maps [Internet]. 2008 [cited 2018 May 27];4(1):108–18. Available from: <http://www.tandfonline.com/action/journalInformation?journalCode=tjom20>
 10. Pikora TJ, Bull FC., Jamrozik K, Knuiman M, Giles-Corti B, Donovan RJ. Developing a reliable audit instrument to measure the physical environment for physical activity. Am J Prev Med [Internet]. 2002 10 1 [cited 2018 May 27];23(3):187–94. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0749379702004981> [PubMed: 12350451]
 11. Kelly CM, Schootman M, Baker EA, Barnidge EK, Lemes A. The association of sidewalk walkability and physical disorder with area-level race and poverty. J Epidemiol Community Health [Internet]. 2007 11 1 [cited 2018 May 27];61(11):978–83. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/17933956> [PubMed: 17933956]
 12. Clifton KJ, Livi Smith AD, Rodriguez D. The development and testing of an audit for the pedestrian environment. Landsc Urban Plan [Internet]. 2007 3 28 [cited 2018 May 27];80(1–2):95–110. Available from: <https://www.sciencedirect.com/science/article/pii/S0169204606001101>
 13. Johnson T, Long T. Determining the frequency of open windows in residences: a pilot study in Durham, North Carolina during varying temperature conditions. J Expo Anal Environ Epidemiol [Internet]. 2005 7 10 [cited 2017 Sep 18];15(4):329–49. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/15536488> [PubMed: 15536488]
 14. Bennett GG, McNeill LH, Wolin KY, Duncan DT, Puleo E, Emmons KM. Safe To Walk? Neighborhood Safety and Physical Activity Among Public Housing Residents Duperrex O, editor. PLoS Med [Internet]. 2007 10 23 [cited 2018 May 27];4(10):e306 Available from: <http://dx.plos.org/10.1371/journal.pmed.0040306>
 15. Wilson DK, Kirtland KA, Ainsworth BE, Addy CL. Socioeconomic status and perceptions of access and safety for physical activity. Ann Behav Med [Internet]. 2004 8 [cited 2018 May 27];28(1):20–8. Available from: <https://academic.oup.com/abm/article/28/1/20-28/4633673> [PubMed: 15249256]
 16. Ou JY, Levy JI, Peters JL, Bongiovanni R, Garcia-Soto J, Medina R, et al. A Walk in the Park: The Influence of Urban Parks and Community Violence on Physical Activity in Chelsea, MA. Int J Environ Res Public Health [Internet]. 2016 1 4 [cited 2018 Sep 7];13(1). Available from: <http://www.ncbi.nlm.nih.gov/pubmed/26742051>
 17. Zannin PHT, Calixto A, Diniz FB, Ferreira JAC. A survey of urban noise annoyance in a large Brazilian city: the importance of a subjective analysis in conjunction with an objective analysis. Environ Impact Assess Rev [Internet]. 2003 3 1 [cited 2018 May 27];23(2):245–55. Available from: <https://www.sciencedirect.com/science/article/pii/S0195925502000926>
 18. Pedersen E, Persson Wayne K. Perception and annoyance due to wind turbine noise—a dose–response relationship. J Acoust Soc Am [Internet]. 2004 12 8 [cited 2018 May 27];116(6):3460–70. Available from: <http://asa.scitation.org/doi/10.1121/1.1815091> [PubMed: 15658697]
 19. Kotel M Survey of occupant behaviour, energy use and indoor air quality in Greenlandic dwellings. 2018 [cited 2018 May 27]; Available from: http://orbit.dtu.dk/files/52204200/Article_16_3_2012.pdf

20. Andersen RV, Toftum J, Andersen KK, Olesen BW. Survey of occupant behaviour and control of indoor environment in Danish dwellings. *Energy Build* [Internet]. 2009;41(1):11–6. Available from: <http://www.sciencedirect.com/science/article/pii/S0378778808001655>
21. Ma L, Dill J. Associations between the objective and perceived built environment and bicycling for transportation. *J Transp Heal* [Internet]. 2015;2(2):248–55. Available from: <http://www.sciencedirect.com/science/article/pii/S2214140515000110>
22. Groves RM. Nonresponse Rates and Nonresponse Bias in Household Surveys. *Public Opin Q* [Internet]. 2006 1 1 [cited 2018 May 27];70(5):646–75. Available from: <http://academic.oup.com/poq/article/70/5/646/4084443/Nonresponse-Rates-and-Nonresponse-Bias-in>
23. Brook JR, Setton EM, Seed E, Shooshtari M, Doiron D. The Canadian Urban Environmental Health Research Consortium – a protocol for building a national environmental exposure data platform for integrated analyses of urban form and health. *BMC Public Health* [Internet]. 2018 12 8 [cited 2018 Apr 4];18(1):114 Available from: <https://bmcpublichealth.biomedcentral.com/articles/10.1186/s12889-017-5001-5> [PubMed: 29310629]
24. Middel A, Lukaszczuk J, Maciejewski R. Sky View Factors from Synthetic Fisheye Photos for Thermal Comfort Routing—A Case Study in Phoenix, Arizona. *Urban Plan* [Internet]. 2017 3 27 [cited 2018 Apr 4];2(1):19 Available from: <http://www.cogitatiopress.com/urbanplanning/article/view/855>
25. Hara K, Sun J, Moore R, Jacobs D, Froehlich JE. Tohme: Detecting Curb Ramps in Google Street View Using Crowdsourcing, Computer Vision, and Machine Learning. 2014 [cited 2018 Apr 4]; Available from: http://kotarohara.com/assets/Papers/Hara_TohmeDetectingCurbRampsInGoogleStreetViewUsingCrowdsourcingComputerVisionAndMachineLearning_UIST2014.pdf
26. Howard-Reed C, Wallace LA, Ott WR. The Effect of Opening Windows on Air Change Rates in Two Homes. *J Air Waste Manage Assoc* [Internet]. 2002 2 [cited 2017 Oct 1];52(2):147–59. Available from: <http://www.tandfonline.com/doi/abs/10.1080/10473289.2002.10470775>
27. Bekö G, Gustavsen S, Frederiksen M, Bergsøe NC, Kolarik B, Gunnarsen L, et al. Diurnal and seasonal variation in air exchange rates and interzonal airflows measured by active and passive tracer gas in homes. *Build Environ* [Internet]. 2016 8 [cited 2017 Apr 18];104:178–87. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0360132316301688>
28. MacNeill M, Wallace L, Kearney J, Allen RW, Van Ryswyk K, Judek S, et al. Factors influencing variability in the infiltration of PM_{2.5} mass and its components. *Atmos Environ* [Internet]. 2012 12 [cited 2017 Apr 18];61:518–32. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S1352231012006772>
29. Rogot E, Sorlie PD, Backlund E. Air-conditioning and mortality in hot weather. *Am J Epidemiol* [Internet]. 1992 7 1 [cited 2018 Jul 11];136(1):106–16. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/1415127> [PubMed: 1415127]
30. O'Neill MS, Zanobetti A, Schwartz J. Disparities by race in heat-related mortality in four US cities: the role of air conditioning prevalence. *J Urban Health* [Internet]. 2005 6 [cited 2018 Jul 11];82(2):191–7. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/15888640> [PubMed: 15888640]
31. Semenza JC, Rubin CH, Falter KH, Selanikio JD, Flanders WD, Howe HL, et al. Heat-Related Deaths during the July 1995 Heat Wave in Chicago. *N Engl J Med* [Internet]. 1996 7 11 [cited 2018 Jul 11];335(2):84–90. Available from: <http://www.nejm.org/doi/abs/10.1056/NEJM199607113350203> [PubMed: 8649494]
32. Curriero FC, Heiner KS, Samet JM, Zeger SL, Strug L, Patz JA. Temperature and mortality in 11 cities of the eastern United States. *Am J Epidemiol* [Internet]. 2002 1 1 [cited 2018 Jul 11];155(1):80–7. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/11772788> [PubMed: 11772788]
33. About Our City | City of Chelsea MA [Internet]. [cited 2018 May 18]. Available from: <https://www.chelseama.gov/about-our-city>
34. U.S. Census Bureau's American Community Survey Office. B01003: Total Population, 2012–2016 American Community Survey 5-Year Estimates [Internet]. United States Census Bureau / American FactFinder 2016 [cited 2018 May 20]. Available from: https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=ACS_16_5YR_B01003&prodType=table

35. Massachusetts Executive Office of Energy and Environmental Affairs. Environmental Justice Policy of the Executive Office of Energy and Environmental Affairs. Boston, Massachusetts; 2017.
36. Klein Rosenthal J, Kinney PL, Metzger KB. Intra-urban vulnerability to heat-related mortality in New York City, 1997–2006. *Health Place* [Internet]. 2014 11 1 [cited 2018 Jul 11];30:45–60. Available from: <https://www.sciencedirect.com/science/article/pii/S1353829214001087#t0030> [PubMed: 25199872]
37. Harlan SL, Brazel AJ, Prashad L, Stefanov WL, Larsen L. Neighborhood microclimates and vulnerability to heat stress. *Soc Sci Med* [Internet]. 2006 12 1 [cited 2018 Jul 11];63(11):2847–63. Available from: <https://www.sciencedirect.com/science/article/pii/S027795360600373X> [PubMed: 16996668]
38. Environmental Systems Research Institute I. Overview - Photo Survey | ArcGIS for Local Government [Internet]. [cited 2018 May 14]. Available from: <http://solutions.arcgis.com/local-government/help/photo-surveys/get-started/>
39. City of Chelsea M Chelsea Property Data [Internet]. chelseama.gov. 2018 [cited 2018 May 20]. Available from: <https://www.chelseama.gov/assessor/pages/chelsea-property-data>
40. Shi S, Zhao B. Occupants' interactions with windows in 8 residential apartments in Beijing and Nanjing, China. 2016 [cited 2017 Sep 18]; Available from: <https://link-springer-com.ezproxy.bu.edu/content/pdf/10.1007%2Fs12273-015-0266-z.pdf>
41. Torres Quezada J, Toshiharu I, Coch Roura H, Isalgue Buxeda A. Predominant factorson Multi-housing overheating interior conditions and body temperature: a field study in Japan. *Int Conf Smart, Sustain Sensuous Settlements Transform Proceeding* [Internet]. 2018 [cited 2018 Jul 10];163–8. Available from: <https://upcommons.upc.edu/handle/2117/117071>
42. Kowaltowski DCK, da Silva VG, Pina SAMG, Labaki LC, Ruschel RC, de Carvalho Moreira D. Quality of life and sustainability issues as seen by the population of low-income housing in the region of Campinas, Brazil. *Habitat Int* [Internet]. 2006 12 1 [cited 2018 Jul 10];30(4):1100–14. Available from: <https://www.sciencedirect.com/science/article/pii/S019739750600021X>
43. Budd T Burglary: Practice Messages from the British Crime Survey [Internet]. London; 2001 [cited 2018 Jul 24]. Available from: <http://library.college.police.uk/docs/hoprcbrf/brf501.pdf>

Figure 1:
One of the two cameras mounted to the car prior to data collection in February 2017.

Figure 2:
Screenshot of a survey from the 2017 winter photo survey in Chelsea, MA.

Figure 3:
Map showing residential parcels in Chelsea, Massachusetts, with at least one window air conditioning (AC) unit identified in the summer 2017 photo survey. Parcels labeled as “No data” are either non-residential parcels or parcels with missing data.

Figure 4: Map showing residential parcels in Chelsea, Massachusetts, with at least one open window identified in the summer 2017 photo survey. Parcels labeled as “No data” are either non-residential parcels or parcels with missing data.

Table 1.

Summary statistics for the parcels captured in the winter and the summer photo surveys compared to all parcels in Chelsea, MA.

Variable	Winter Survey Parcels	Summer Survey Parcels	Chelsea, MA
Photo Survey			
Total Number of Parcels	969	1 213	4 877 (3 494 residential)
Mean Number of Stories (SD)	2.7 (0.66)	2.7 (0.76)	2.2
American Community Survey¹			
Median Household Income (SD)	\$48 548 (\$15 296)	\$48 548 (\$14 825)	\$49 614
Mean % Non-Hispanic White (SD)	29.0% (17.9%)	25.0% (17.4%)	23.2%
Mean % with Bachelor's/Associate's Degree (SD)	15.3% (7.6%)	15.0% (8.7%)	12.7%
Mean % Unemployed (SD)	7.3% (6.4%)	8.2% (7.0%)	7.5%
Mean % Renter-Occupied (SD)	67.3% (19.8%)	70.8% (17.9%)	73.9%
Median Monthly Rent (SD)	\$1 200 (\$220)	\$1 210 (\$190)	\$1 193
Mean % English Language Only (SD)	37.5% (16.0%)	33.1% (17.6%)	30.1%
Assessors Database			
Mean Year Built (SD)	1917 (29.4)	1915 (28.3)	1917
Single Family, %	20.5%	16.7%	17.3%
Two Family, %	29.0%	28.3%	24.7%
Three Family, %	21.0%	21.2%	19.2%
Apartment Building, %	9.0%	8.5%	6.6%
Condominium, %	4.8%	6.8%	4.3%
Store or Shop, %	3.9%	3.7%	3.7%

¹Data from the American Community Survey were reported at the block group-level and we assigned these values to the captured parcels within each block group. The summary statistics reported above are the averages across all captured parcels.

Table 2.

Results of the crowdsourced surveys for both the winter and summer photo surveys.

	Winter Survey	Summer Survey
Temperature Range During Photo Collection	2.2-8.9°C	24.4-26.7°C
Weather Conditions	Sunny and warmer in afternoon	Sunny then overcast; small shower in afternoon
% residential parcels with open windows (total)	18.8%	52.6%
% residential parcels with open windows on:		
Any floor but top floor	5.7%	19.5%
Top floor and another floor	4.3%	14.9%
Top floor only	8.8%	18.1%
Top floor only (excluding 1-story buildings)	9.0%	18.2%
% residential parcels with an AC Unit	20.9%	68.8%
% of total parcels with an open window and an AC unit	4.8%	38.3%
Number (%) of parcels with an open window and AC unit, by residence type		
Single Family	9 (4.5%)	67 (33.2%)
Two Family	9 (3.2%)	121 (35.3%)
Three Family	11 (5.4%)	98 (38.1%)
Apartment Building	5 (5.7%)	56 (54.4%)
Condominium	2 (4.4%)	27 (32.9%)
Store or Shop	3 (7.9%)	19 (42.2%)