Associations of Spatial Mobility with Sexual Risk Behaviors among Young Men Who Have Sex with Men in New York City: A Global Positioning System (GPS) Study

Byoungjun Kim, Seann D. Regan, Denton Callander, William C. Goedel, Basile Chaix, Dustin T. Duncan

Associations of Spatial Mobility with Sexual Risk Behaviors among Young Men Who Have Sex with Men in New York City: A Global Positioning System (GPS) Study

Byoungjun KIM, MUP [1]

Seann D. REGAN, MA [1]

Denton CALLANDER, PhD [1]

William C. GOEDEL, BA [2]

Basile CHAIX, PhD [3]

Dustin T. DUNCAN, ScD [1]

[1.] Department of Epidemiology, Columbia University Mailman School of Public Health, New York, New York, United States

[2.] Department of Epidemiology, School of Public Health, Brown University, Providence, Rhode Island, USA

[3.] Sorbonne Université, INSERM, Institut Pierre Louis d'Epidémiologie et de Santé Publique IPLESP, Nemesis team, F75012 Paris, France

Address Correspondence to: Byoungjun Kim, MUP, Columbia University Mailman School of Public Health, Department of Epidemiology, Social and Spatial Epidemiology Unit, 722 West 168th Street, New York, NY 10032. Email: bk2767@cumc.columbia.edu

Abstract

Spatial contexts and spatial mobility are important factors on the HIV epidemic and sexually transmitted infections. Using global positioning system (GPS) devices, we examined the associations of objectively measured spatial mobility with sexual risk behaviors among gay, bisexual and other men who have sex with men (MSM) in New York City. This observational study included a subgroup of 253 HIV-negative MSM from the Project 18 Cohort Study, who participated in the GPS monitoring sub-study. Spatial mobility was measured as (1) distance traveled and (2) activity space size defined as daily path area during 2-week of GPS tracking. We examined the associations of these measures with numbers of male sexual partners and condomless anal intercourse (CAI) acts during last six months using quasi-Poisson models, adjusting for socio-demographics. Results demonstrated that spatial mobility was positively associated with sexual risk behaviors, for example, with CAI (incidence rate ratio [IRR] = 1.01 for a 10 km increase in distance traveled and IRR=1.04 for a 1 km^2 increase in 50m-buffer activity space size). Our findings may enhance the understanding of spatial contexts of HIV risk. Future studies should be conducted to examine the mechanisms for the associations between spatial mobility behaviors with sexual risk behaviors as well as the influence of neighborhood characteristics in various neighborhood contexts, which may guide the place-based HIV prevention services.

Keywords: spatial analysis; mobility; Global Positioning System (GPS); sexual behavior; Men who have Sex with Men (MSM); HIV prevention;

Introduction

The incidence rate of human immunodeficiency virus (HIV) is disproportionately high among gay, bisexual and other men who have sex with men (MSM), especially young MSM. In 2018, MSM accounted for 69.6% of new HIV cases among adult and adolescent (age over 13 years) in the United States (U.S.), and young MSM (aged 13 to 29 years old) made up 48.6% of new HIV infections among MSM (Centers for Disease Control and Prevention, 2019). Furthermore, even though HIV incidence in the general population in the U.S. has decreased since 2008, the rate among MSM during 2008-2015 remained high and even increased by 5.7% per year among MSM between age 25 and 34 (Singh et al., 2018).

In addition to standard individual-level sociodemographic factors affecting vulnerability to HIV infection, geographic factors such as the spatial mobility behavior and characteristics of spatial contexts have been studied to explain variations in HIV incidence in heterosexual population as well as among MSM. Theoretical and empirical studies have identified that spatial mobility, including migration, commuting, and local mobility, is one of important factors influencing HIV transmission (Vaughan et al., 2017, Cassels and Camlin, 2016, Cassels et al., 2017, Deane et al., 2010, Coffee et al., 2007, Camlin et al., 2013). The theoretical frameworks suggested multiple pathways that may explain the associations between mobility and HIV risks. Mobile individuals may have potentials to be connected to riskier sexual network with larger number of partners in different places (Cassels et al., 2017). In addition, non-residential places may be separated from conventional HIV prevention supports and have higher risk of environmental exposures (Frye et al., 2014, Vaughan et al., 2017). Lastly, exposure to diverse non-residential contexts may increase HIV risk, since lack of social-monitoring and non-kin ties in the neighborhoods may facilitate more frequent engagement in sexual risk behaviors (Seeley and Allison, 2005, Camlin et al., 2013). To illustrate, previous studies have demonstrated that highly mobile men are more likely to be engaged in risky sexual behaviors, such as more frequent engagement in condomless sex and having increased number of sexual partners (Saggurti et al., 2008, Saggurti et al., 2009, Lydie et al., 2004, Kishamawe et al., 2006, Khan et al., 2008, Gupta et al., 2010, Schuyler et al., 2017). However, most of the studies on local daily mobility and HIV infection have investigated heterosexual populations in African or low-income countries, and only a handful of studies have assessed the role of spatial mobility in the context of the HIV epidemic among MSM in the U.S. (Mustanski et al., 2015, Tobin et al., 2013)

The spatial context of risk behaviors may also be salient to MSM population in the U.S., since studies have shown that MSM experience different types of neighborhoods (Koblin et al., 2017, Tobin et al., 2014, Koblin et al., 2013, Duncan et al., 2014), and thus may have differential influences from diverse neighborhood environments. Two recent studies have shown that few MSM reside, socialize, and meet sexual partners in the same neighborhoods (Koblin et al., 2013, Duncan et al., 2014). Young MSM are especially likely to have higher degree of spatial mobility compared to general MSM, due to the developmental characteristics of this age group during their transition to adulthood (Schachter, 2001). In addition, MSM with higher mobility may experience different venues to meet their sexual partners, and such diverse venues play important role in shaping sexual risk behaviors (Al-Ajlouni et al., 2018a, Young et al., 2017).

The scant research on spatial mobility behavior and HIV among MSM has examined a limited measure of mobility, mostly relying on self-reported mobility, raising concerns of recall bias and misclassification. Objective measures of mobility and spatial context are increasingly used in the field of physical activity and obesity research (Jia et al., 2019, James et al., 2016, Chaix et al., 2013), but not widely applied in HIV epidemiology. Use of global positioning system (GPS) technologies is an objective approach to investigate the aspects of spatial mobility by allowing researchers to identify participants' continuous spatial location over time. Such spatio-temporal data can be used to measure local daily mobility and construct activity spaces, and these data, in conjunction with survey data, can measure time and duration of different types of neighborhood exposures (Duncan et al., 2016). GPS technologies present an opportunity to enhance understandings of the relationship between personal spatial mobility behavior and HIV risk among MSM population.

As such, the purpose of this study was to investigate the association of spatial mobility behavior measured using GPS, with sexual risk behaviors among young MSM. In the present study, we hypothesize that more mobile young MSM may have higher numbers of sexual partners and more frequently engage in condomless anal intercourse.

Method

P18 Neighborhood Study

The present study recruited participants of the *Project 18 Cohort Study*, a prospective cohort study of 665 HIV-negative MSM in New York City designed to study longitudinal trajectories of sexual behavior, substance use, and mental health among young MSM (Halkitis et al., 2013). Venue-based (e.g., community events, afterschool events, service agencies, public spaces, and nightlife venues) and internet-based (e.g., social networking and dating websites) recruitments was employed for the original cohort. Both active (e.g., approaching individuals to solicit study participation) and passive (e.g., flyers, advertising on internet) methods were used for the participant recruitment. Inclusion criteria for the original cohort were: (a) age 18 to 19 years old; (b) male sex assignment at birth; (c) currently identify as male; (d) residence in the New York City metropolitan area; (e) report sexual contact with another man in the preceding six months; and (f) reported negative or unknown HIV status. The study started from May 2009. We randomly sorted the 665 P18 Cohort participants and invited them to the sub-study, known as the P18 Neighborhood Study. We contacted to the randomly sorted participants via email or text messaging until the number of enrollments was reached to 250. Total 450 participants were contacted, and the 250 participants enrolled in the sub-study between January 2017 and January 2018. The response rate was 56%. Additional eligibility criteria were applied for the subgroup study, including (1) having no mobility restrictions through a screening question, "Do you have serious difficulty walking or climbing stairs?", (2) being comfortable carrying a GPS device for two weeks, and (3) being able to come in for the first and follow-up visits. The selected sub-group of 250 participants showed similar socio-demographics with the original cohort. For example, the percentages of Black/African-American in the sub-cohort and the original cohort were 30% and 27% respectively (White: 32% vs. 25%; Asian: 10% vs. 8%, school enrollment: 25% vs 33%, less than high school:34% vs. 39%; Associate: 11% vs 13%; College: 55% vs. 48%) (Jaiswal et al., 2018).

At the first visit, participants were consented to the subgroup study, completed the first survey, and received instructions on GPS device. At the follow-up visit, they returned the GPS device, completed an exit survey, and were compensated $110. Three participants did not complete the two visits, therefore, three additional participants were randomly selected and enrolled in the sub-study. The University Committee on Activities Involving Human Subjects at New York University and the institutional review board of the New York University School of Medicine approved the research protocol prior to subject enrollment.

GPS Protocol

Participants were asked to carry a small GPS device (BT-Q1000XT, QStarz International Co., Ltd., Taipei, Taiwan) at all times over a two-week period, except when sleeping, swimming, and showering. The device collected location data in 10-second intervals, and additional GPS-use diary was used to evaluate the GPS data quality. Feasibility and acceptability of proposed GPS protocol was tested from a prior pilot study (Duncan et al., 2016), and a similar protocol was applied for this study. Of total 250 participants with GPS data, 39 participants were excluded as they (1) lived outside of New York City, (2) had invalid addresses, and/or (3) had less than 1 hour of GPS data for one day, which did not meet the data quality protocol. A total of 211 participants were used in the analysis. GPS data cleaning used a set of processing scripts to eliminate erroneous data, such as duplicated time stamps and isolated GPS points. Spatially isolated points were identified using 400-meter distance between two consecutive points (10 second apart), and those points were removed from the dataset.

Geographic Mobility Calculation

To quantify the local daily mobility of participants, we employed two measures; distance traveled and activity space size (Figure 1). The distance traveled was measured using inter-point distance calculation, and for the activity spaces, daily path area calculation was employed (Boruff et al., 2012, Sherman et al., 2005, Hirsch et al., 2014, Duncan et al., 2018b). The daily path area was defined by creating 50, 100, 200, and 400-meter buffering radiuses around the GPS points in New York City. We selected 50-meter buffer activity space as the main metric of exposure, based on the line-of sight theory and existing studies on GPS-based activity space. It is suggested that micro street-level features may impact on how individuals perceive and interact with the urban context (Llobera, 2003, Ewing et al., 2006), thus we assumed that the 50-meter buffer can effectively capture the street-level environments, especially in the settings of New York City. In addition, previous studies on GPS-based mobility described that the 50-buffer can avoid potential dependence of the urban environmental characteristics between consecutive points when assessing neighborhood exposures from walking activity (Rodriguez et al., 2012, Troped et al., 2010). As the estimates may be sensitive to the sizes of buffer due to the modifiable areal unit problem (Wong, 2009), we also ran sensitivity analyses for different buffer sizes, and reported in the supplement table. The activity space sizes (i.e., the sizes of the daily path area) were expressed in square kilometers (km^2), based on Universal Transverse Mercator (UTM) zone 18N projection, one of two-dimensional Cartesian coordinate systems corresponding to New York City metropolitan area. All GPS data processing and cleaning were conducted using ESRI ArcGIS 10.4 and Quantum QGIS 2.6.

Sexual behavior outcomes

In this study, we focused on sexual behaviors associated with risk of HIV infection among MSM. The Project 18 Cohort Study collected data on sexual behaviors including number of male sexual partners and number of condomless sexual encounters in past six months. The number of male sexual partners was assessed from two questions: (1) “In the past 6 months, how many male steady partners have you have anal or oral sex with?,” (2) “In the past 6 months, how many casual male partners have you had anal or oral sex with?". The total number from those two questions was used as one outcome and was considered a count type variable in the analyses (Koblin et al., 2006, Vittinghoff et al., 1999, Page-Shafer et al., 1997, Kuiken et al., 1990, Darrow et al., 1987). In addition, numbers and types of sexual encounters were assessed to create three variables: total numbers of condomless anal intercourse (CAI) acts, (2) total numbers of condomless insertive anal intercourse (CIAI) acts, and (3) total number of condomless receptive anal intercourse (CRAI) acts in past six months (Patel et al., 2014, Koblin et al., 2006, Vittinghoff et al., 1999, Page-Shafer et al., 1997, Kuiken et al., 1990, Darrow et al., 1987).

Covariates

Participants reported their socio-demographic characteristics, such as age (years), ethnicity (Hispanic or non-Hispanic), and race (Black, Asian, White, and others), education attainment (high school or less, some college/ technical school, college degree or more), current school enrollment status (yes/no), and foreign-born status (yes/no). Homelessness was also included in the analyses, as it is an important factor of mobility and risk behaviors (Aidala et al., 2005). Self-reported total individual annual income was categorized as less than $15,000, between $15,000 and $35,000, more than $35,000 per year, which approximates national poverty level (<$15,000) (U.S. Department of Health and Human Services, 2017). The national poverty level is criterion of various social support programs, such as Supplemental Nutrition Assistance Program (SNAP) and Home Energy Assistance Program (HEAP), thus the categorical value may reflect people who were eligible for such programs (Falk and Aussenberg, 2013).

Other potential confounders were included: drug use (any type of substance in any form except marijuana) in the past 6-month (yes/no), numbers of alcoholic drinks in the past 30 days, and number of days of experiencing mental health problems (stress, depression, and emotional problems in the past 30 days). In addition, participants' sexual identification (gay or bisexual) and relationship status (currently having a main romantic partner), were included in the analyses (Harawa et al., 2008, Everett, 2013, Mustanski et al., 2011, Hoff et al., 2012).

Lastly, residential self-selection of individual, which describes that people choose where to live based on their travel needs and preferences, may influence the mobility patterns and health behaviors (Boone-Heinonen et al., 2011, Mokhtarian and Cao, 2008), thus two ordinal variables were included: (1) "How important was housing price to you when choosing to live in your current neighborhood?" and (2) "How important was living in the city center to you when choosing to live in your current neighborhood?". Response options for the two questions were (1) not at all important, (2) not too important, (3) somewhat important, (4) mostly important, and (5) very important. All abovementioned variables were included in the multivariate models.

Statistical Analyses

Descriptive statistics were generated to summarize data of the study. In order to identify associations between spatial mobility and sexual risk behaviors, quasi-Poisson regression models were fitted with a logarithmic link function, and for CAI, CIAI, and CRAI models, total number of anal intercourse acts was included as an offset variable. We examined bivariate and multivariable models of different mobility measures with covariates. Adjusted multivariate models were fitted with abovementioned covariates. Lastly, we tested effect modification between the exposure and two potential modifiers (sexual identification and relationship status) using multiplicative interaction terms. All estimates are presented with 95% confidence intervals (CIs). All statistical analyses were conducted using R.3.3.2 with built-in functions including "glm" for quasi-Poisson modeling.

Results

Socio-demographic characteristics of participants are shown on Table 1. The average distance traveled during the two-week monitoring period was 400.9 kilometers and the size of activity spaces for 50, 100, 200, and 400 m buffers were 6.0 km^2, 9.4 km^2, 16.3 km^2, 29.2 km^2, respectively. Participants reported an average of 5.6 male sexual partners in the past six months (standard deviation [SD]: 7.1). Over the same period, participants engaged in CAI an average of 15.1 times (SD: 25.9), including 8.3 CIAI acts (SD: 18.1) and 7.0 CRAI acts (SD: 13.8). The sample was relatively young (mean age of 24.9, SD=0.9) and mostly gay (84%). The participants were diverse in terms of race/ethnicity; 32% White, 30% Black, 17% others, 10% Asian; and 30% Hispanic/Latino.

Table 2 describes the results of quasi-Poisson models for the associations between distance traveled and sexual risk behaviors. From the multivariate models, distance traveled during the two-week period was not associated with the number of male sexual partners. The total distance traveled was associated with CAI acts and CIAI acts. The number of CAI acts increased by 1% per additional 10 kilometers traveled (IRR: 1.01, 95% CI: 1.00–1.02) and the number of CIAI acts increased by 2% from the full models.

Table 3 shows model results with activity space size, measured as 50m buffer daily path area. Activity space size was associated with the number of male sexual partners from the full model (IRR:1.04, CI: 1.00-1.08). Activity space size was associated with the number of CAI acts (IRR:

1.04, CI: 1.01-1.06). In particular, the number of CIAI acts increased by 5% (IRR: 1.05; 95% CI: 1.01–1.09) for each additional square kilometer increase in activity space size as defined with a 50-meter buffer from the full model. The number of CRAI acts was not associated with the activity space size from the full model. The association of interest between activity space size and sexual risk behaviors tended to decrease, as the radius considered defining the daily path area was larger (Supplemental Table 1), yet the direction of coefficients and confidence intervals remain consistent with main findings.

The coefficients of covariates showed similar directions and trends from both the distance travelled and the activity space size models (Table 2 and 3). Drug use was positively associated with the number of sexual partners, presence of romantic partner was positively associated with CAI. Increased age was associated with higher numbers of CIAI. Alcohol use was negatively associated with CIAI, while it is positively associated with CRAI. School enrollment status and presence of romantic partner were strong and positive predictors of CRAI.

Lastly, the multivariate models with multiplicative interaction terms showed no interactions between geographic mobility and the two potential effect modifiers; sexual identification and presence of romantic partner (data not shown).

Discussion

This study examined mobility-related correlates of sexual risk behaviors among a sample of HIV-negative young MSM in New York City. From our models, we found that higher local daily mobility, defined as longer distance traveled and larger activity space sizes, was correlated with increased total numbers of CAI acts. Despite the relatively small effect sizes, these finding suggest that local daily mobility is predictor of sexual behaviors of young MSM in New York City.

Spatial mobility may be related to sexual risk networks, as greater mobility may be associated with expanded sexual networks (Cassels et al., 2017, Vaughan et al., 2017). Formation of sexual networks is linked to spatial mobility, and people with greater spatial mobility are likely to develop more social ties in different places (Gesink et al., 2019, Belot and Ermisch, 2009, Carrasco et al., 2008, Larsen et al., 2006). The total number of CAI may also be related to potential engagement in risky sexual networks in different places. Our findings are consistent with existing findings on mobility and risk of HIV infection. Previous studies found that MSM with high mobility were at higher risk for HIV infection (Ramesh et al., 2014, Mustanski et al., 2015) and MSM who travel for leisure engage in more frequent sexual risk behaviors than those who do not (Benotsch et al., 2006b, Benotsch et al., 2006a, Benotsch et al., 2011, Harry-Hernandez et al., 2019).

In addition, personality may play an important role in determining both mobility and sexual risk behaviors. Under this hypothesis, the mobility measures would reflect aspects of the personality that are also related to sexual risk behaviors (e.g., a preference for new and exciting experiences may lead an individual to meet sexual partners in different neighborhoods and a proclivity for CAI). However, it should be mentioned that visiting several places with sexual purposes during the GPS observation period might have contributed to increased local daily mobility. To illustrate, large proportions of young MSM in the U.S. uses diverse range of social networking smartphone applications to meet male partners, and such internet or app-users may be more likely to have higher mobility compared to non-users (Duncan et al., 2018a, Benotsch et al., 2011, Card et al., 2018). The latter particular case does not correspond to a causal effect of spatial mobility behavior on sexual risk behavior.

This study is not without limitations. First, study was conducted in New York City, and the participants were sampled from HIV-negative and mobile young MSM. Thus, our findings may not be generalizable to other environments, such as small cities and rural areas, and other MSM populations including HIV-positive, older, or disabled. Second, the measured mobility does not capture the content of experiences of participants within neighborhoods. In other words, we did not investigate the characteristics of neighborhood exposures, such as social and physical features of neighborhoods that participants visited or the types of places that participants visited and related activities. Studies suggest that the venue of partner meeting plays role in shaping sexual risk behaviors (Al-Ajlouni et al., 2018b, Grov et al., 2007, Colfax et al., 2001), however, the increased spatial mobility did not reflect actual exposures to risky environments, rather it may indicate longer commutes or travel routes Previous studies suggested that higher mobility may be associated with lack of conventional social supports for HIV prevention (Frye et al., 2014, Vaughan et al., 2017), however, we was not able to ascertain the differential social environments of diverse neighborhood exposures. Also, although the two-week monitoring period is relatively long compared to most health studies using GPS (Duncan et al., 2018b), the measured mobility assessed over the period may not represent participants' typical travel behaviors. However, a recent study by Zenk et al reported that a two-week period is adequate to measure individual travel behavior (Zenk et al., 2018). Third, the GPS protocol was designed for 2-week data collection, but not all of participants engaged in the full-period tracking. We did not standardize the distance traveled and activity space size by number of days of tracking. Fourth, GPS signal errors and data losses may be introduced due to special settings in large metropolitan locations such as subway, underground, and large buildings (Georgiadou and Kleusberg, 1988). Despite the GPS error, we processed the data to maximize reliability by eliminating isolated points and duplicated timestamps. Lastly, there are several limitations inherent in any cross-sectional survey including difficulties to infer causality. We were not able to examine temporal association between the mobility behaviors and sexual risk behaviors, and so it remains possible as discussed above that sexual risk behaviors, especially the willingness to have a large number of partners, may have influenced the size of the activity space captured over the monitoring period due to participants travelling to meet their sexual partners.

Our study also has numerous strengths, including assessing the objective measure of local daily mobility, a large sample size for a sensor-based study, and a relatively long period of GPS tracking period (Zenk et al., 2018, Duncan et al., 2018b). To our knowledge, this study is the largest GPS study to examine the association between objectively measured mobility and sexual risk behaviors in any MSM population. The GPS protocol allowed 10-second epochs, which high monitoring frequency enhanced the overall quality of the GPS data. Moreover, the two-week monitoring period was longer than most existing GPS studies that typically monitor participants over one week, capturing more variations of travel behavior of participants, and is a significant step forward beyond place-based analysis based on residential administrative boundaries such as census tracts or ZIP codes.

As noted above, further studies should be conducted to examine the effects of different neighborhoods and meeting venues including residential, work, social, and sexual contexts to understand actual influences of neighborhoods. In addition, temporal dimensions (e.g. duration) of exposure can be tested with the GPS data to test dose-response associations. Social and physical characteristics of the various neighborhoods will have to be considered, on the basis of the GPS data that we collected, for instance population density, HIV prevalence, crime rates, neighborhood disorder, racial segregation, and proximity to clinical and social services (Duncan et al., Forthcoming). One could test psychosocial factors and social network characteristics that may shape sexual health behaviors, in order to increase our level of understanding of the impact of socio-spatial contexts on the sexual risk behaviors. Additionally, GPS-based ecological momentary assessment (EMA) method will be helpful to better understand the actual exposures to neighborhood characteristics (Duncan et al., 2019). Lastly, longitudinal studies should be conducted to investigate causal influences over time of spatial mobility behavior and socio-spatial contexts on sexual risk behaviors.

Conclusions

Our innovative study found that local daily mobility was associated with sexual risk behaviors, confirming the role of geographic mobility in the context of the HIV epidemic among MSM in the U.S. Future research should seek to understand the impacts of different types of neighborhoods and places visited on HIV risk behaviors using this mobility-based approaches in order to enhance place-based HIV prevention by allowing specific target places for interventions.

Reference

AIDALA, A., CROSS, J. E., STALL, R., HARRE, D. & SUMARTOJO, E. 2005. Housing status and HIV risk behaviors: implications for prevention and policy. *AIDS Behav,* 9**,** 251-65.

AL-AJLOUNI, Y. A., PARK, S. H., SCHNEIDER, J. A., GOEDEL, W. C., HAMBRICK, H. R., HICKSON, D. A., CANTOR, M. N. & DUNCAN, D. T. 2018a. Partner meeting venue typology and sexual risk behaviors among French men who have sex with men. *International Journal of Std & Aids,* 29**,** 1282-1288.

AL-AJLOUNI, Y. A., PARK, S. H., SCHNEIDER, J. A., GOEDEL, W. C., RHODES HAMBRICK, H., HICKSON, D. A., CANTOR, M. N. & DUNCAN, D. T. 2018b. Partner meeting venue typology and sexual risk behaviors among French men who have sex with men. *Int J STD AIDS,* 29**,** 1282-1288.

BARAL, S., LOGIE, C. H., GROSSO, A., WIRTZ, A. L. & BEYRER, C. 2013. Modified social ecological model: a tool to guide the assessment of the risks and risk contexts of HIV epidemics. *Bmc Public Health,* 13.

BELOT, M. & ERMISCH, J. 2009. Friendship ties and geographical mobility: evidence from Great Britain. *Journal of the Royal Statistical Society Series a-Statistics in Society,* 172**,** 427-442.

BENOTSCH, E. G., MARTIN, A. M., ESPIL, F. M., NETTLES, C. D., SEAL, D. W. & PINKERTON, S. D. 2011. Internet Use, Recreational Travel, and HIV Risk Behaviors in Men Who Have Sex With Men. *Journal of Community Health,* 36**,** 398-405.

BENOTSCH, E. G., MIKYTUCK, J. J., RAGSDALE, K. & PINKERTON, S. D. 2006a. Sexual risk and HIV acquisition among men who have sex with men travelers to Key West, Florida: A mathematical modeling analysis. *Aids Patient Care and Stds,* 20**,** 549-556.

BENOTSCH, E. G., SEELEY, S., MIKYTUCK, J. J., PINKERTON, S. D., NETTLES, C. D. & RAGSDALE, K. 2006b. Substance use, medications for sexual facilitation, and sexual risk behavior among traveling men who have sex with men. *Sexually Transmitted Diseases,* 33**,** 706-711.

BOODRAM, B., HOTTON, A. L., SHEKHTMAN, L., GUTFRAIND, A. & DAHARI, H. 2018. High-Risk Geographic Mobility Patterns among Young Urban and Suburban Persons who Inject Drugs and their Injection Network Members. *Journal of Urban Health-Bulletin of the New York Academy of Medicine,* 95**,** 71-82.

BOONE-HEINONEN, J., GORDON-LARSEN, P., GUILKEY, D. K., JACOBS, D. R. & POPKIN, B. M. 2011. Environment and physical activity dynamics: The role of residential self-selection. *Psychology of Sport and Exercise,* 12**,** 54-60.

BORUFF, B. J., NATHAN, A. & NIJËNSTEIN, S. 2012. Using GPS technology to (re)-examine operational definitions of ‘neighbourhood’in place-based health research. *International journal of health geographics,* 11**,** 22.

CAMLIN, C. S., KWENA, Z. A. & DWORKIN, S. L. 2013. Jaboya Vs. Jakambi: Status, Negotiation, and Hiv Risks among Female Migrants in the "Sex for Fish" Economy in Nyanza Province, Kenya. *Aids Education and Prevention,* 25**,** 216-231.

CARD, K. G., GIBBS, J., LACHOWSKY, N. J., HAWKINS, B. W., COMPTON, M., EDWARD, J., SALWAY, T., GISLASON, M. K. & HOGG, R. S. 2018. Using Geosocial Networking Apps to Understand the Spatial Distribution of Gay and Bisexual Men: Pilot Study. *JMIR Public Health Surveill,* 4**,** e61.

CARRASCO, J. A., MILLER, E. J. & WELLMAN, B. 2008. How Far and with Whom Do People Socialize? Empirical Evidence About Distance Between Social Network Members. *Transportation Research Record***,** 114-122.

CASSELS, S. & CAMLIN, C. S. 2016. Geographical mobility and heterogeneity of the HIV epidemic. *Lancet Hiv,* 3**,** E339-E341.

CASSELS, S., JENNESS, S. M., BINEY, A. A. E. & DODOO, F. N. A. 2017. Geographic mobility and potential bridging for sexually transmitted infections in Agbogbloshie, Ghana. *Social Science & Medicine,* 184**,** 27-39.

CENTERS FOR DISEASE CONTROL AND PREVENTION 2015. 2016 HIV Surveilance: HIV and Young Men Who Have Sex with Men.

CENTERS FOR DISEASE CONTROL AND PREVENTION 2019. HIV Surveillance Reports: Diagnoses of HIV Infection in the United States and Dependent Areas, 2018 (Preliminary).

CHAIX, B., MELINE, J., DUNCAN, S., MERRIEN, C., KARUSISI, N., PERCHOUX, C., LEWIN, A., LABADI, K. & KESTENS, Y. 2013. GPS tracking in neighborhood and health studies: A step forward for environmental exposure assessment, a step backward for causal inference? *Health & Place,* 21**,** 46-51.

COFFEE, M., LURIE, M. N. & GARNETT, G. P. 2007. Modelling the impact of migration on the HIV epidemic in South Africa. *Aids,* 21**,** 343-350.

COLFAX, G. N., MANSERGH, G., GUZMAN, R., VITTINGHOFF, E., MARKS, G., RADER, M. & BUCHBINDER, S. 2001. Drug use and sexual risk behavior among gay and bisexual men who attend circuit parties: A venue-based comparison. *Journal of Acquired Immune Deficiency Syndromes,* 28**,** 373-379.

DARROW, W. W., ECHENBERG, D. F., JAFFE, H. W., O'MALLEY, P. M., BYERS, R. H., GETCHELL, J. P. & CURRAN, J. W. 1987. Risk factors for human immunodeficiency virus (HIV) infections in homosexual men. *Am J Public Health,* 77**,** 479-83.

DEANE, K. D., PARKHURST, J. O. & JOHNSTON, D. 2010. Linking migration, mobility and HIV. *Tropical Medicine & International Health,* 15**,** 1458-1463.

DUNCAN, D., KIM, B., AL-AJLOUNI, Y. & CALLANDER, D. Forthcoming. Neighborhood-Level Structural Factors, HIV and Communities of Color. *In:* OJIKUTU, B. & STONE, V. (eds.) *HIV/AIDS in US communities of color.* 2n Edition ed.: Springer.

DUNCAN, D. T., KAPADIA, F. & HALKITIS, P. N. 2014. Examination of Spatial Polygamy among Young Gay, Bisexual, and Other Men Who Have Sex with Men in New York City: The P18 Cohort Study. *International Journal of Environmental Research and Public Health,* 11**,** 8962-8983.

DUNCAN, D. T., KAPADIA, F., REGAN, S. D., GOEDEL, W. C., LEVY, M. D., BARTON, S. C., FRIEDMAN, S. R. & HALKITIS, P. N. 2016. Feasibility and Acceptability of Global Positioning System (GPS) Methods to Study the Spatial Contexts of Substance Use and Sexual Risk Behaviors among Young Men Who Have Sex with Men in New York City: A P18 Cohort Sub-Study. *PLoS One,* 11**,** e0147520.

DUNCAN, D. T., PARK, S. H., GOEDEL, W. C., SHEEHAN, D. M., REGAN, S. D. & CHAIX, B. 2019. Acceptability of smartphone applications for global positioning system (GPS) and ecological momentary assessment (EMA) research among sexual minority men. *PLoS One,* 14**,** e0210240.

DUNCAN, D. T., PARK, S. H., HAMBRICK, H. R., DANGERFIELD, D. T., GOEDEL, W. C., BREWER, R., MGBAKO, O., LINDSEY, J., REGAN, S. D. & HICKSON, D. A. 2018a.

Characterizing Geosocial-Networking App Use Among Young Black Men Who Have Sex With Men: A Multi-City Cross-Sectional Survey in the Southern United States. *Jmir Mhealth and Uhealth,* 6.

DUNCAN, D. T., REGAN, S. D. & CHAIX, B. 2018b. Operationalizing neighborhood definitions in health research: Spatial misclassification and other issues. *Neighborhoods and Health.* Oxford University Press.

EVERETT, B. G. 2013. Sexual Orientation Disparities in Sexually Transmitted Infections: Examining the Intersection Between Sexual Identity and Sexual Behavior. *Archives of Sexual Behavior,* 42**,** 225-236.

EWING, R., HANDY, S., BROWNSON, R. C., CLEMENTE, O. & WINSTON, E. 2006. Identifying and Measuring Urban Design Qualities Related to Walkability. *J Phys Act Health,* 3**,** S223-S240.

FALK, G. & AUSSENBERG, R. 2013. The Supplemental Nutrition Assistance Program: categorical eligibility. Congressional Research Service.

FRYE, V., EGAN, J. E., TIEU, H. V., CERDA, M., OMPAD, D. & KOBLIN, B. A. 2014. "I didn't think I could get out of the fucking park." Gay men's retrospective accounts of neighborhood space, emerging sexuality and migrations. *Social Science & Medicine,* 104**,** 6-14.

GEORGIADOU, Y. & KLEUSBERG, A. 1988. On carrier signal multipath effects in relative GPS positioning. *Manuscripta geodaetica*, 13**,** 172-179.

GESINK, D., SALWAY, T., KIMURA, L., CONNELL, J., WIDENER, M. & FERLATTE, O. 2019. The Social Geography of Partner Selection in Toronto, Canada: A Qualitative Description of "Convection Mixing". *Archives of Sexual Behavior*.

GROV, C., PARSONS, J. T. & BIMBI, D. S. 2007. Sexual risk behavior and venues for meeting sex partners: An intercept survey of gay and bisexual men in LA and NYC. *Aids and Behavior,* 11**,** 915-926.

GUPTA, K., VAIDEHI, Y. & MAJUMDER, N. 2010. Spatial Mobility, Alcohol Use, Sexual Behavior and Sexual Health Among Males in India. *Aids and Behavior,* 14**,** 18-30.

HALKITIS, P. N., KAPADIA, F., SICONOLFI, D. E., MOELLER, R. W., FIGUEROA, R. P., BARTON, S. C. & BLACHMAN-FORSHAY, J. 2013. Individual, psychosocial, and social correlates of unprotected anal intercourse in a new generation of young men who have sex with men in New York City. *Am J Public Health,* 103**,** 889-95.

HARAWA, N. T., WILLIAMS, J. K., RAMAMURTHI, H. C., MANAGO, C., AVINA, S. & JONES, M. 2008. Sexual behavior, sexual identity, and substance abuse among low-income bisexual and non-gay-identifying African American men who have sex with men. *Archives of Sexual Behavior,* 37**,** 748-762.

HARRY-HERNANDEZ, S., PARK, S. H., MAYER, K. H., KRESKI, N., GOEDEL, W. C., HAMBRICK, H. R., BROOKS, B., GUILAMO-RAMOS, V. & DUNCAN, D. T. 2019. Sex Tourism, Condomless Anal Intercourse, and HIV Risk Among Men Who Have Sex With Men. *Janac-Journal of the Association of Nurses in Aids Care,* 30**,** 405-414.

HIRSCH, J. A., WINTERS, M., CLARKE, P. & MCKAY, H. 2014. Generating GPS activity spaces that shed light upon the mobility habits of older adults: a descriptive analysis. *International journal of health geographics,* 13**,** 51.

HOFF, C. C., CHAKRAVARTY, D., BEOUGHER, S. C., NEILANDS, T. B. & DARBES, L. A. 2012. Relationship Characteristics Associated with Sexual Risk Behavior Among MSM in Committed Relationships. *Aids Patient Care and Stds,* 26**,** 738-745.

JAISWAL, J., GRIFFIN, M., SINGER, S. N., GREENE, R. E., ACOSTA, I. L. Z., KAUDEYR, S. K., KAPADIA, F. & HALKITIS, P. N. 2018. Structural Barriers to Pre-exposure Prophylaxis Use Among Young Sexual Minority Men: The P18 Cohort Study. *Current Hiv Research,* 16**,** 237-249.

JAMES, P., JANKOWSKA, M., MARX, C., HART, J. E., BERRIGAN, D., KERR, J., HURVITZ, P. M., HIPP, J. A. & LADEN, F. 2016. "Spatial Energetics" Integrating Data From GPS, Accelerometry, and GIS to Address Obesity and Inactivity. *American Journal of Preventive Medicine,* 51**,** 792-800.

JIA, P., XUE, H., YIN, L., STEIN, A., WANG, M. Q. & WANG, Y. F. 2019. Spatial Technologies in Obesity Research: Current Applications and Future Promise. *Trends in Endocrinology and Metabolism,* 30**,** 211-223.

JOHNSON, A. S., HALL, H. I., HU, X., LANSKY, A., HOLTGRAVE, D. R. & MERMIN, J. 2014. Trends in diagnoses of HIV infection in the United States, 2002-2011. *JAMA,* 312**,** 432-4.

KHAN, M. R., PATNAIK, P., BROWN, L., NAGOT, N., SALOUKA, S. & WEIR, S. S. 2008. Mobility and HIV-related sexual behavior in Burkina Faso. *Aids and Behavior,* 12**,** 202-212.

KISHAMAWE, C., VISSERS, D. C. J., URASSA, M., ISINGO, R., MWALUKO, G., BORSBOOM, G. J. J. M., VOETEN, H. A. C. M., ZABA, B., HABBEMA, J. D. F. & DE VLAS, S. J. 2006. Mobility and HIV in Tanzanian couples: both mobile persons and their partners show increased risk. *Aids,* 20**,** 601-608.

KOBLIN, B. A., EGAN, J. E., NANDI, V., SANG, J. M., CERDA, M., TIEU, H. V., OMPAD, D. C., HOOVER, D. R. & FRYE, V. 2017. Congruence of Home, Social and Sex

Neighborhoods among Men Who Have Sex with Men, NYCM2M Study. *Journal of Urban Health-Bulletin of the New York Academy of Medicine,* 94**,** 364-374.

KOBLIN, B. A., EGAN, J. E., RUNDLE, A., QUINN, J., TIEU, H. V., CERDA, M., OMPAD, D. C., GREENE, E., HOOVER, D. R. & FRYE, V. 2013. Methods to Measure the Impact of Home, Social, and Sexual Neighborhoods of Urban Gay, Bisexual, and Other Men Who Have Sex with Men. *Plos One,* 8.

KOBLIN, B. A., HUSNIK, M. J., COLFAX, G., HUANG, Y. J., MADISON, M., MAYER, K., BARRESI, P. J., COATES, T. J., CHESNEY, M. A. & BUCHBINDER, S. 2006. Risk factors for HIV infection among men who have sex with men. *Aids,* 20**,** 731-739.

KUIKEN, C. L., VAN GRIENSVEN, G. J., DE VROOME, E. M. & COUTINHO, R. A. 1990. Risk factors and changes in sexual behavior in male homosexuals who seroconverted for human immunodeficiency virus antibodies. *Am J Epidemiol,* 132**,** 523-30.

LARSEN, J., URRY, J. & AXHAUSEN, K. W. 2006. *Mobilities, networks, geographies,* Aldershot, England ; Burlington, VT, Ashgate.

LLOBERA, M. 2003. Extending GIS-based visual analysis: the concept of visualscapes. *International Journal of Geographical Information Science,* 17**,** 25-48.

LYDIE, N., ROBINSON, N. J., FERRY, B., AKAM, E., DE LOENZIEN, M., ABEGA, S. & HIV, S. G. O. H. O. 2004. Mobility, sexual behavior, and HIV infection in an urban population in Cameroon. *Jaids-Journal of Acquired Immune Deficiency Syndromes,* 35**,** 67-74.

MOKHTARIAN, P. L. & CAO, X. Y. 2008. Examining the impacts of residential self-selection on travel behavior: A focus on methodologies. *Transportation Research Part B-Methodological,* 42**,** 204-228.

MUSTANSKI, B., BIRKETT, M., KUHNS, L. M., LATKIN, C. A. & MUTH, S. Q. 2015. The Role of Geographic and Network Factors in Racial Disparities in HIV Among Young Men Who have Sex with Men: An Egocentric Network Study. *AIDS and Behavior,* 19**,** 1037-1047.

MUSTANSKI, B., NEWCOMB, M. E. & CLERKIN, E. M. 2011. Relationship characteristics and sexual risk-taking in young men who have sex with men. *Health Psychology,* 30**,** 597.

PAGE-SHAFER, K., VEUGELERS, P. J., MOSS, A. R., STRATHDEE, S., KALDOR, J. M. & VAN GRIENSVEN, G. J. 1997. Sexual risk behavior and risk factors for HIV-1 seroconversion in homosexual men participating in the Tricontinental Seroconverter Study, 1982-1994. *Am J Epidemiol,* 146**,** 531-42.

PATEL, P., BORKOWF, C. B., BROOKS, J. T., LASRY, A., LANSKY, A. & MERMIN, J. 2014. Estimating per-act HIV transmission risk: a systematic review. *AIDS,* 28**,** 1509-19.

RAMESH, S., MEHROTRA, P., MAHAPATRA, B., GANJU, D., NAGARAJAN, K. & SAGGURTI, N. 2014. The effect of mobility on sexual risk behaviour and HIV infection: a cross-sectional study of men who have sex with men in southern India. *Sexually Transmitted Infections,* 90**,** 491-+.

RHODES, T. & SIMIC, M. 2005. Transition and the HIV risk environment. *British Medical Journal,* 331**,** 220-223.

RODRIGUEZ, D. A., CHO, G. H., EVENSON, K. R., CONWAY, T. L., COHEN, D., GHOSH-DASTIDAR, B., PICKREL, J. L., VEBLEN-MORTENSON, S. & LYTLE, L. A. 2012. Out and about: Association of the built environment with physical activity behaviors of adolescent females. *Health & Place,* 18**,** 55-62.

SAGGURTI, N., SCHENSUL, S. L. & VERMA, R. K. 2009. Migration, Mobility and Sexual Risk Behavior in Mumbai, India: Mobile Men with Non-Residential Wife Show Increased Risk. *Aids and Behavior,* 13**,** 921-927.

SAGGURTI, N., VERMA, R. K., JAIN, A., RAMARAO, S., KUMAR, K. A., SUBBIAH, A., MODUGU, H. R., HALLI, S. & BHARAT, S. 2008. HIV risk behaviours among contracted and non-contracted male migrant workers in India: potential role of labour contractors and contractual systems in HIV prevention. *Aids,* 22**,** S127-S136.

SCHACHTER, J. 2001. Geographical Mobility: Population Characteristics. *Current Population Reports, US Census Bureau, Washington, DC.*

SCHUYLER, A. C., EDELSTEIN, Z. R., MATHUR, S., SEKASANVU, J., NALUGODA, F., GRAY, R., WAWER, M. J., SERWADDA, D. M. & SANTELLI, J. S. 2017. Mobility among youth in Rakai, Uganda: Trends, characteristics, and associations with behavioural risk factors for HIV. *Global Public Health,* 12**,** 1033-1050.

SEELEY, J. A. & ALLISON, E. H. 2005. HIV/AIDS in fishing communities: Challenges to delivering antiretroviral therapy to vulnerable groups. *Aids Care-Psychological and Socio-Medical Aspects of Aids/Hiv,* 17**,** 688-697.

SHERMAN, J. E., SPENCER, J., PREISSER, J. S., GESLER, W. M. & ARCURY, T. A. 2005. A suite of methods for representing activity space in a healthcare accessibility study. *Int J Health Geogr,* 4**,** 24.

SINGH, S., SONG, R., JOHNSON, A. S., MCCRAY, E. & HALL, H. I. 2018. HIV Incidence, Prevalence, and Undiagnosed Infections in U.S. Men Who Have Sex With Men. *Ann Intern Med,* 168**,** 685-94.

TEMPALSKI, B. & MCQUIE, H. 2009. Drugscapes and the role of place and space in injection drug use-related HIV risk environments. *International Journal of Drug Policy,* 20**,** 4-13.

TOBIN, K. E., CUTCHIN, M., LATKIN, C. A. & TAKAHASHI, L. M. 2013. Social geographies of African American men who have sex with men (MSM): A qualitative exploration of the social, spatial and temporal context of HIV risk in Baltimore, Maryland. *Health & Place,* 22**,** 1-6.

TOBIN, K. E., LATKIN, C. A. & CURRIERO, F. C. 2014. An examination of places where African American men who have sex with men (MSM) use drugs/drink alcohol: A focus on social and spatial characteristics. *International Journal of Drug Policy,* 25**,** 591-597.

TROPED, P. J., WILSON, J. S., MATTHEWS, C. E., CROMLEY, E. K. & MELLY, S. J. 2010. The Built Environment and Location-Based Physical Activity. *American Journal of Preventive Medicine,* 38**,** 429-438.

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES 2017. 2017 Poverty Guidelines.

VAUGHAN, A. S., KRAMER, M. R., COOPER, H. L. P., ROSENBERG, E. S. & SULLIVAN, P. S. 2017. Activity spaces of men who have sex with men: An initial exploration of geographic variation in locations of routine, potential sexual risk, and prevention behaviors. *Social Science & Medicine,* 175**,** 1-10.

VITTINGHOFF, E., DOUGLAS, J., JUDSON, F., MCKIRNAN, D., MACQUEEN, K. & BUCHBINDER, S. P. 1999. Per-contact risk of human immunodeficiency virus transmission between male sexual partners. *American Journal of Epidemiology,* 150**,** 306-311.

WONG, D. 2009. The modifiable areal unit problem (MAUP). *In:* FOTHERINGHAM, A. S. & ROGERSON, P. A. (eds.) *The SAGE handbook of spatial analysis.* London: SAGE.

YOUNG, L. E., MICHAELS, S., JONAS, A., KHANNA, A. S., SKAATHUN, B., MORGAN, E., SCHNEIDER, J. A. & TEAM, U. S. 2017. Sex Behaviors as Social Cues Motivating Social Venue Patronage Among Young Black Men Who Have Sex with Men. *Aids and Behavior*, 21**,** 2924-2934.

ZENK, S. N., MATTHEWS, S. A., KRAFT, A. N. & JONES, K. K. 2018. How many days of global positioning system (GPS) monitoring do you need to measure activity space environments in health research? *Health & Place*, 51**,** 52-60.

Table 1. Socio-demographic characteristics, activity space size, and sexual risk behaviors, The P18 Neighborhood Study (n=211)

Variables	Levels	Mean (SD) or N (%)
Age	In years, min=23, max=26	24.9 (0.9)
Race	White	67 (32%)
	Black/African American	64 (30%)
	Others	35 (17%)
	Asian	21 (10%)
	Two or more	21 (10%)
Ethnicity	Non-Hispanic/Latino	148 (70%)
	Hispanic/Latino	63 (30%)
Annual income (total, individual)	<$15,000	51 (24%)
	$15,000 - $35,000	70 (33%)
	>$35,000	76 (36%)
Current student	Yes	52 (25%)
Education	≤ High School	71 (34%)
	Associate	23 (11%)
	College/Graduate	116 (55%)
Homeless	Yes	7 (3%)
Foreign-born	Yes	30 (14%)
Drug use in the past 6 months	Yes	101 (48%)
Alcohol use in the past 30 days	Number of drinks	8.3 (7.5)
Experience of mental health issues	Number of days	5.0 (7.5)
Sexual identity	Gay	177 (84%)
	Bisexual	30 (14%)
Relationship type	Has a romantic partner	77 (36%)
Distance traveled	(in km^2)	400.9 (224.9)
Importance of price in current housing choice	Not at all important	13 (6%)
	Nott too important	4 (2%)
	Somewhat important	39 (18%)
	Mostly important	45 (21%)
	Very important	92 (44%)
Importance of being city center in current housing choice	Not at all important	25 (12%)
	Nott too important	55 (26%)
	Somewhat important	59 (28%)
	Mostly important	33 (16%)
	Very important	27 (13%)
50m activity space size	(in km^2)	6.0 (5.1)
100m activity space size	(in km^2)	9.4 (8.2)
200m activity space size	(in km^2)	16.3 (14.1)
400m activity space size	(in km^2)	29.2 (24.3)
Number of male sexual partners	In the past 6 months	5.6 (7.1)
Number of CAI	In the past 6 months	15.1 (25.9)
Number of CIAI	In the past 6 months	8.3 (18.1)
Number of CRAI	In the past 6 months	7.0 (13.8)

SD: standard deviation,
CAI: condomless anal intercourse,
CIAI: condomless insertive anal intercourse,
CRAI: condomless receptive anal intercourse