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Gendered impacts of public transport on social isolation and loneliness among older adults: Evidence from a natural experiment in Hong Kong

Guibo Sun [a,*], Yao Du [b], Tim Schwanen [c]

[a] Department of Planning, Property and Environmental Management, The University of Manchester, United Kingdom
[b] Department of Social Work and Social Administration, The University of Hong Kong, Hong Kong, China
[c] Transport Studies Unit, University of Oxford, United Kingdom

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ABSTRACT

A well-designed public transport system has the potential to support social participation and alleviate social isolation and loneliness among older adults. However, limited research has explored whether such benefits differ between older men and women. Using a natural experiment involving a new metro line in Hong Kong, our cohort study (N = 449) of older people yields a surprising finding: contrary to previous studies suggesting that women are more likely than men to experience social isolation and loneliness, our analysis reveals that older men report higher levels of both. Despite this, the new metro line has not significantly reduced social isolation or loneliness among older men. In contrast, older women have actively engaged with the new metro line, especially for those with greater social participation at the baseline, leveraging it to strengthen their social networks and mitigate social isolation and loneliness. These findings suggest that public transport may not equally benefit all groups, underscoring the importance of considering gender differences, particularly the needs of older men, in transport planning to reduce social isolation and loneliness.

1. Introduction

People worldwide are living longer. By 2030, one in six people globally will be aged 60 or older, with this population projected to rise from 1 billion in 2020 to 1.4 billion. By 2050, it is projected to double to 2.1 billion (WHO, 2024). Public transport systems could play a crucial role in promoting social participation and reducing social isolation and loneliness, particularly among older adults (Du et al., 2022a; Wang et al., 2023). As policymakers, researchers, communities, and families increasingly prioritise later-life well-being, addressing the risks of loneliness and isolation has become an urgent issue for cities with ageing populations. In addition, the population of older men is growing faster than that of older women. For instance, in Europe, the number of older men aged 65 or above living alone increased by 35 % between 2014 and 2023, with Denmark experiencing a more substantial rise of 70 %, which significantly heightens vulnerability to isolation (Eurostat, 2024). Similarly, many Asian cities are projected to experience rapid ageing in the coming decades (Sun and Musselwhite, 2025). Understanding and addressing men's unique experiences of loneliness and social isolation thus becomes especially crucial (Schutter et al., 2022). While public transport plays a critical role in facilitating access to essential services and interactions, little is known about whether gender influences how older adults experience changes in loneliness and isolation. An understanding of this relationship would be valuable for effective public transport interventions.

Social isolation and loneliness are not inevitable consequences of the ageing process. Loneliness refers to a perception of feeling alone, whereas social isolation denotes the absence of contact with others (Steptoe et al., 2013). Both social isolation and loneliness have consistently been linked to adverse health and well-being outcomes, including increased risk of morbidity, functional decline, and mental health issues (Luo et al., 2012). Social isolation can be measured by the size of social networks, which tend to shrink in later life due to life transitions (e.g., retirement) or age-related losses (e.g., the death of family members) (Coyle and Dugan, 2012; Du et al., 2022a; Lee et al., 2021). Previous studies have found that older adults with small social networks are at increased risk of all-cause mortality (Berkman, 1995; Courtin and Knapp, 2017). Loneliness has been identified as a significant precursor to depression and hypertension among older adults (Van Beljouw et al., 2014). It is also associated with reduced physical activity, poor

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* Corresponding author. Humanities Bridgeford Street, The University of Manchester, Oxford Road, Manchester, M15 6PB, United Kingdom.
E-mail addresses: guibo.sun@manchester.ac.uk (G. Sun), yaodu@hku.hk (Y. Du), tim.schwanen@ouce.ox.ac.uk (T. Schwanen).

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nutrition, insomnia, and a higher likelihood of admission to residential care facilities (Ong et al., 2016).

Public transport could be crucial in addressing social isolation and loneliness among older people. It can provide essential connectivity to social networks, family, friends, and communities, enabling older adults to maintain mobility and independence (Musselwhite et al., 2015). By facilitating access to social activities, public transport could help prevent social isolation and loneliness (Stanley et al., 2011). This is especially the case in the often overlooked yet unique dynamics of Asian cities, where older adults primarily rely on public transport. Unlike in car-dominated regions, such as the U.S., for instance, older people use cars for about 84–91 % of trips—their travel by walking and transit declines sharply after age 75 (Boschmann and Brady, 2013). Conversely, in Asian high-density cities like Hong Kong, older adults account for over 90 % of daily trips via public transport, thanks to a well-developed and affordable system (Du et al., 2022b); The challenge lies not in shifting from cars to public transport but in ensuring that public transport systems cater to the specific needs of older people (Hsieh, 2024; Sun and Musselwhite, 2025). Improving public transport is widely regarded as a strategy for promoting well-being and reducing social isolation among older adults (Cochran, 2020; Du and Sun, 2024; Stanley et al., 2011). Recognising the impact of transport on social exclusion, the UK government developed accessibility planning guidance for local authorities to acknowledge the role of transportation in reducing social disadvantage (Lucas, 2012). However, research often overlooks the specific potential of public transport in addressing social isolation and loneliness. Although related, social isolation and loneliness are distinct from social exclusion, which encompasses broader issues of marginalisation and deprivation (Mackett and Thoreau, 2015). The understanding of how public transport interventions can strengthen social connections by enhancing the mobility of older adults remains limited (Hemingway and Jack, 2013; Preston and Rajé, 2007; Sun and Du, 2023). It is worth noting that most transport planning does not explicitly address health and well-being outcomes in transport infrastructure provision, often rendering health outcomes as side effects (Ogilvie et al., 2020a, 2020b). Practice-based evidence about the health and well-being effects of infrastructure changes can deepen our understanding and support the design of evidence-based transport interventions (Sun and Musselwhite, 2025).

Public transport both shapes and is shaped by city- and neighbourhood-level built environments. Healthy-cities research typically organises these contexts via the D-variables—density, diversity (land-use mix), and design—augmented by metropolitan factors such as destination accessibility and distance to transit. In monocentric settings, city-level centrality remains a key determinant of commuting (Næss, 2025), and in many European and North American cities, greater distance from the centre often aligns with weaker transit and fewer amenities (Mouratidis, 2018). However, these regularities are not universal. High-density Asian cities exhibit different built environment–travel behaviour relationships. Hong Kong's ultra-dense, rail-oriented form, for example, alters how density and centrality relate to mode choice and trip length, with heterogeneity by population group (younger adults vs. older adults), trip purpose (work vs. non-work), and mode (car vs. public transport; bus vs. metro, with metro dominant). For commuters, city-centre accessibility significantly influences mode choice and trip length, while for older adults, local accessibility—nearby services (healthcare, markets, amenities) and barrier-free routes—more strongly predicts public transport use and supports social participation and independent living. Neighbourhood features also condition older adults' transit use: fine-grained pedestrian networks and seamless station access facilitate metro adoption, whereas elevated or deep underground access can suppress walk access and ridership (Sun and Lau, 2021). These contrasts suggest caution in transferring evidence from European/North American contexts to Asian cities for research related to ageing and mobility. The distinctive densities, rail reliance (e.g., Hong Kong, Tokyo), and ageing-related needs underscore the value of context-sensitive theorising and measurement in the effects of public transport on health and wellbeing outcomes (Sun and Musselwhite, 2025).

Gender, life stages, and mobility are deeply interconnected and play a critical role in shaping experiences of social isolation and loneliness (Umberson et al., 2022). However, relatively little research has explored how changes in social isolation and loneliness in response to public transport interventions might differ by gender among older people. Older men and women often maintain social networks differently, and previous studies have identified notable gender differences in loneliness (Pinquart and Sörensen, 2001). Women tend to cultivate close friendships outside the family and have more frequent interactions with relatives (Schutter et al., 2022). They also tend to participate more actively in community activities, such as in the context of Hong Kong (Du et al., 2022a). In contrast, men typically form broader but less intimate connections that become less frequent as they age. Furthermore, men commonly rely on workplace friendships, which may diminish significantly after retirement. They often report higher levels of social isolation due to reduced contact with children, family members, and friends. These gendered patterns influence how public transport interventions impact social isolation and loneliness. Additionally, influenced by norms around hegemonic masculinity, older men are generally less likely to seek medical or emotional support. When older men do experience loneliness, they are at a greater risk of severe outcomes, including depression and suicide, compared to women (Zebhauser et al., 2014). By recognising how gender and mobility intersect during later life stages, targeted interventions can be designed to promote equity, strengthen social connections, and improve population health outcomes (Sun and Musselwhite, 2025; Wang et al., 2023). The gendered patterns on mobility, social isolation and loneliness underpin our study and highlight the importance of addressing gender-specific needs in public transport planning.

Experimental studies are essential for determining whether a public transport intervention has led to meaningful changes in health and well-being outcomes (Sun et al., 2020, 2023). Such studies can enhance our understanding of effective interventions and illuminate the mechanisms through which these interventions work. However, experimentally altering transport infrastructure to assess its effects poses significant challenges, as doing so is often impractical or unethical (Ogilvie et al., 2020a). Additionally, researchers typically have limited control over the design or modification of transport services (Sun et al., 2020). Consequently, existing evidence regarding the relationship between transport, social isolation, and loneliness primarily relies on identifying associations through statistical modelling rather than establishing the causal relationships that experimental studies can demonstrate (Aldred et al., 2019; Schwanen, 2018; Sun et al., 2023).

A natural experiment that leverages opportunities arising from newly introduced transportation changes could offer a valuable approach to estimating plausible causal effects of public transport on social isolation and loneliness (Sun and Musselwhite, 2025). Several studies have employed natural experiments to examine the relationship between transport and health behaviours (Humphreys et al., 2016; Kärmeniemi et al., 2018). However, previous studies often lack rigorous research designs that define control groups and enable treatment-control group assignments that resemble those of randomised controlled experiments (McCormack et al., 2021; Sun et al., 2014; Wali et al., 2022; Xie et al., 2021). Researchers typically rely on statistical modelling techniques to infer causality. Such causal inferences may be less convincing due to difficulties in validating complex modelling assumptions (e.g., structural equation models and dose-effect analyses) or excluding unobservable confounders (Freedman, 1999). Incorporating transport planning knowledge into the design of natural experiments, particularly by understanding how infrastructure interventions are planned and implemented, can help address challenges associated with treatment-control group assignment (He et al., 2022; Sun et al., 2023). However, such domain-specific knowledge has rarely been integrated into natural experiment research designs within the transport and health literature (Sun and Musselwhite, 2025).

In this paper, we present a natural experimental study that utilises a new metro line in Hong Kong to estimate the effects of public transport on social isolation and loneliness among a cohort of older adults, with a particular focus on gender differences. Our case study, Hong Kong, is quickly becoming an ageing society: the population aged 65 or above is projected to increase from 1.45 million (21 %) in 2021 to 2.74 million (33 %) by 2046. Through this case study, we aim to explore whether new metro lines, like those recently developed in many high-density cities in Asia, differentially affect older men's and women's sense of social connectivity. We incorporate local metro planning knowledge to enhance comparability between treatment and control groups. Using cohort data and a natural experiment, we provide credible causal evidence on the gendered impacts of public transport on social isolation and loneliness among older adults.

2. Methods

2.1. Natural experiment design

The longitudinal data of travel behaviour, social isolation and loneliness of a cohort of older people were obtained from the Metro and Elderly Health in Hong Kong study, which is a natural experiment research project to investigate the effects of a new metro line on public transport use and wider health outcomes (Sun et al., 2021a). Hong Kong represents a typical high-density Asian urban context characterised by mixed land-use patterns, densely populated residential areas, a well-developed public transport system, and easy access to most amenities. In Hong Kong, public transport accounts for over 90 % of all mechanised trips. As of 2022, buses accounted for approximately 32.1 % of total public transport trips, making them the city's second-largest public transport mode (Transport Department, 2023). In recent years, Hong Kong has progressively expanded its metro system, resulting in corresponding adjustments to bus services, including the introduction of feeder routes to metro stations and the cancellation of routes parallel to the metro lines (Du et al., 2022b).

2.1.1. Intervention

The intervention examined in this study is a new metro line. Between 2007 and 2024, the metro network grew from 212 km with 84 stations to over 270 km with 99 stations, and the government plans to double this capacity by 2050. The recent metro intervention analysed here involves a new line comprising eight stations connecting Tai Wai to Hung Hom Station. Four of these eight stations are newly constructed, while the remaining four have been modified by adding new platforms, exits, and improved transfer connections. This significant infrastructure intervention aims to enhance public transport reliability, reduce congestion-related delays, and improve overall travel experiences in a high-density urban environment.

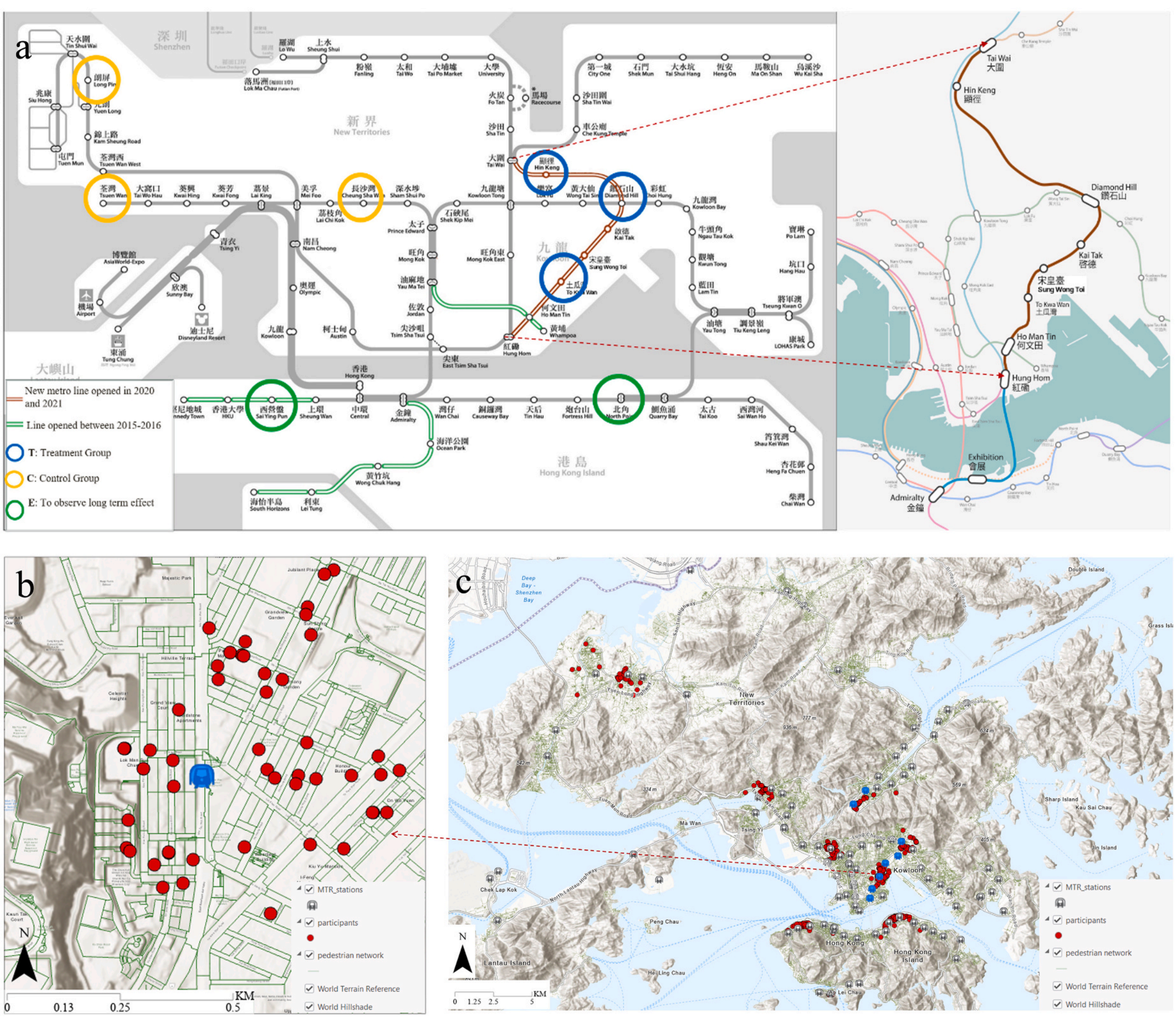

Fig. 1. Study design and participants: (a) Intervention and treatment-control group assignment (b) Distribution of participants around the new metro station (To Kwa Wan, treatment group). (c) Overall distribution of study participants.

2.1.2. Treatment-control assignment

Fig. 1 shows the treatment–control group assignment. Three treatment groups were from the new metro line (highlighted in blue circles in Fig. 1). Participants were older adults living within approximately 400 m of the new stations' exits. In Hong Kong, a metro station can have multiple exits, often extended by footbridges and underground passages, so the 400 m buffer is a rough guideline for participant recruitment. Three control groups consist of participants residing in station catchments with comparable residential neighbourhood types, regional accessibility, socioeconomic status, and demographics, where the stations have been operating for over 15 years (highlighted in yellow in Fig. 1). We also designed two other groups on Hong Kong Island (highlighted in green circles in Fig. 1) that were not exposed to the new metro. Sai Ying Pun station entered service in 2015, while North Point station has been in operation for over three decades. We aimed to compare the longitudinal data of participants from Sai Ying Pun station with those from North Point station to investigate any long-term effects.

The assignment of treatment and control groups followed an as-if random logic grounded in the historical planning and financing context of the metro system, rather than in characteristics related to older people's health and wellbeing outcomes. As established in (Sun and Du, 2023), the control group serves as the counterfactual, enabling estimation of changes that would have occurred in the absence of the intervention. Hong Kong's metro development was guided by the rail-plus-property financing model, whereby infrastructure construction depended on financial viability tied to land value uplift (Aveline-Dubach and Blandeau, 2019). The treatment and control lines were planned concurrently in 1967 under similar design, demographic, development potential and policy conditions (Loo et al., 2018). However, the treatment line experienced cancellation, reinstatement (e.g., in 2002), and prolonged delay due to financial feasibility challenges and institutional factors, including competition and eventual merger between metro operators (Cheung, 2006). These disruptions were administrative and financial in nature, unrelated to population health needs or targeting of specific groups. This sequencing resulted in comparable areas receiving infrastructure at different times for reasons exogenous to resident health, supporting the as-if random assumption. To further reduce residential self-selection bias, only participants with at least three years of residence in their neighbourhoods were included in the study sample.

2.1.3. Cohort data of older people

Our analysis for this paper is based on the cohort data of 449 older people, with 387 participants from the treatment-control groups. The additional 62 cohort participants were recruited for analysing long-term effects and robustness tests. Participants were eligible, subject to the geographic constraints described above, if they were aged 65 or older, Cantonese-speaking, residents in the neighbourhoods for at least three years, and able to walk independently for at least 15 min. The Neighbourhood Elderly Centres helped us verify if the candidates met our recruiting criteria. To avoid biased responses, trained interviewers administered the face-to-face survey using a structured questionnaire. Our baseline survey was conducted before the new metro opened in 2019, and the follow-up survey was conducted from December 2021 to January 2022 after the new metro had been operating for half a year. Ethical approval for the study was obtained from the Human Research Ethics Committee of the University (reference number: EA1710040), and each participant provided written informed consent.

2.2. Measures

2.2.1. Exposure

The exposure was membership in the treatment (1) or control (0) group. The treatment groups were exposed to the metro intervention described in Section 2.1.2.

2.2.2. Social isolation and loneliness

Social isolation was measured by the 6-item Lubben Social Network Scale (Lubben et al., 2006). Participants reported the frequency and amount of their social contact with friends and family members, as well as the perceived social support they obtained from these sources, within the past six months. The total score was calculated by summing all items, which ranged from 0 to 30. A higher score indicates a higher level of social engagement. We also estimated the change in social isolation by subtracting the scores at the baseline survey from the follow-up.

Loneliness was measured by the three-item version of the UCLA Loneliness Scale, which covers three domains: relational connectedness, social connectedness, and self-perceived isolation (Russell, 1996). Participants were asked how often they felt they lacked companionship, were left out, and were isolated from others (hardly ever = 1, some of the time = 2, often = 3) in the past six months (Hughes et al., 2004). We summed each score to create a score of 3–9, with a higher score indicating a greater feeling of loneliness. Changes in loneliness were calculated by subtracting the baseline survey scores from the follow-up scores.

2.2.3. Built environment covariates

Built environment characteristics were generated using a Geographic Information System (ArcGIS Pro, Esri) for the 400 m pedestrian network buffer from each participant's home. In the city's high-density, mixed-use environment, local studies commonly employ a 400-m buffer to assess amenities (e.g., open spaces) and walkability (Tang et al., 2021; Zhao et al., 2020). We collected participants' addresses in the questionnaire, specifying the building in which each participant resided. We then geocoded these locations (see example in Fig. 1b) to extract measures of the surrounding built environment. Note that this study focuses on the interventions brought by the new metro line, so our measurement of the built environment is based on station-area levels and neighbourhood scales, rather than the city level. Another consideration is Hong Kong's unique urban form, consisting of linear corridors with limited built-up areas confined between mountains and the sea. These linear corridors align closely with the metro lines they serve (Xue and Sun, 2021). While previous studies examine how various built environment factors influence social networks, isolation, and loneliness (Boessen et al., 2018), this study focuses specifically on the effects of the public transport intervention, leveraging the natural experiment provided by the new metro line.

The selection of covariates was based on the "5D" framework (density, diversity, design, destination accessibility, and distance to transit) (Sun et al., 2018). These included (1) population density, extracted from population census data in 2021. In Hong Kong, streets demarcated the block census tract unit, and population census data contained the number of household members. Therefore, we calculated the population size of each buffer based on the number of blocks covered by the network. Population density could be linked to the size of the opportunity pool of potential social contacts (Boessen et al., 2018). (2) the density of pedestrian network intersection, representing the design of the 3D pedestrian network in Hong Kong (Sun et al., 2021b). The network is visualised by the green lines in Fig. 1b. The city is connected by extensive footbridges, underground passages, and pathways inside buildings (e.g., shopping malls). (3) average walk score was on a scale of 0–100, based on junctions of networks and amenities junction; (4) the destination diversity, which depict land use patterns based on fourteen types of POI categories (e.g., commercial, retail, and education) (Sun et al., 2018). Unlike research on land use mix, which is a dominant focus in Western city context, the intensity of destinations cannot be measured solely by land use but rather by their functions (amenities) in Hong Kong as a single street or even a building can serve multiple purposes, such as office, residential, and commercial uses (Boessen et al., 2018; Bruyns et al., 2020). The score was calculated by an entropy index, ranging from 0 (homogeneous land use) to 1 (equal mix of land use); and (5) the distance to transit, which was calculated as the walking distance from the respondent's home to the nearest metro station entrance after the new metro line, based on the pedestrian network.

2.2.4. Individual characteristics

Individual factors included participants' baseline weekly public transport use time, physical activity, age (65–100), gender (men, women), monthly income (0–10,000 HKD), education level (middle school and below, high school and above), marital status (married, single/divorced/widowed), the years of residency (3–60), self-reported chronic disease (yes, no) and self-reported mental health (0–100). By including the year of residency, we can control for potential residential self-selection (where people select their residential location based on travel preferences).

2.3. Analysis

Our analyses were conducted using difference-in-difference (DID) modelling. DID method is suitable for our natural experiment research design as it compares changes over time between treatment and control groups, controlling for unobserved individual differences and common trends. It assumes that unobserved characteristics are fixed and that outcomes in both groups would change similarly in the absence of the intervention (Craig et al., 2012). We first examined the treatment effects of the metro intervention on two measures of social isolation (social network and loneliness). The DID model is specified as follows:

$$Y_{it} = \beta_0 + \beta_1\ Treatment_i + \beta_2\ Time_t + \beta_3\ Treatment_i \times Time_t + \beta_4\ Covariates_{it} + \varepsilon_{ij}$$

where Y_{it} is the outcome of social isolation or loneliness for individual i at time t, $Treatment_i$ is a dummy variable that indicates whether individual i is in the treatment group, $Time_t$ is a dummy variable that indicates the time-fixed effect. The DID estimate is β_3, which measures the treatment effects of the metro intervention. A value greater than 0 and significant β_3 would suggest that the new metro positively affects older people's social isolation and loneliness level in treatment groups. $Covariates_{it}$ include environmental and individual factors. ε_{ij} is the error term.

Next, to explore potential gender-specific effects, we estimated the models separately for men and women. Additionally, we divided the dataset into four subgroups based on baseline social isolation and loneliness scores: below-average and above-average. Separate DID models were then applied to each subgroup to assess whether the effects of the intervention differed by initial levels of social isolation and loneliness. Additionally, a three-way interaction term (Time × Treatment × Gender) was also introduced to the main model to formally test whether the intervention's effect differed significantly between men and women.

Finally, we applied DID models to estimate plausible long-term effects of metro interventions on social isolation and loneliness. We compared participants from Sai Ying Pun station (which had been operational for 4 years at the time of the baseline survey) with those from North Point station (operational for over three decades) (Fig. 1, areas highlighted by green circles). If no significant differences emerged in the changes in social isolation and loneliness between these two stations, it could suggest that the effects of metro interventions stabilise approximately four years after the operation begins. This analysis provides insights into the potential temporal effects associated with metro expansions. Additionally, we tested the robustness of our primary DID results by incorporating these two station groups into the control group.

We standardised all variables using z-score standardisation before entering them into the models. All analyses were conducted using Stata (version 17, StataCorp).

3. Results

3.1. Descriptive statistics

Table 1 presents the descriptive statistics for all variables. In the control group, social network sizes declined between baseline and follow-up for both men and women, while loneliness scores increased for both genders. In contrast, within the treatment group, men's social networks slightly expanded, while women's networks showed a modest increase. Loneliness scores in the treatment group slightly decreased for men and remained stable for women. Changes in weekly public transport usage differed by gender in both groups. In the treatment group, women increased their usage more substantially (from 196.26 to 244.44 min) than men (219.35 to242.51 min). Conversely, in the control group, women reduced their use of public transport more than men.

Neighbourhood characteristics—including population density, street intersection density, and walkability scores—remained unchanged from baseline to follow-up in both groups. However, compared to the control areas, the treatment areas exhibited higher population density and greater street intersection density but lower walkability scores. Other individual characteristics, such as marital status, education, and physical activity, were comparable across both groups.

3.2. DID analysis

3.2.1. Metro intervention on social isolation

Table 2 shows the DID results for social networks and loneliness. For social networks, the coefficient of the interaction term (*Time × Treatment*) was positive and significant ($p < 0.05$) in Model 1 and remained significant after adjusting for covariates (Model 2). This suggests that the treatment effect increased by 0.32 standard deviations after the metro intervention. We observed a weak treatment effect for loneliness in Model 3 ($p < 0.10$). The coefficient of the interaction term is significant and negative after adjustments, indicating that the new metro prevented and decreased loneliness (Coefficient = −0.24; $p < 0.05$).

Regarding covariates, destination accessibility was associated with more extensive social network sizes and lower loneliness levels. More physical activity and less chronic disease were associated with increased social networks. Being married, having a higher level of physical activity, and having a higher level of mental health were more likely to have lower loneliness levels. Overall, levels of explained variance (R^2) are modest, but adding the covariates improves the model fit.

3.2.2. DID models stratified by gender and age

Table 3 presents the results of subgroup analyses for social networks. Stratified models assess whether the effects of the metro intervention differ by gender via the Time × Treatment interaction term. Among older men, neither ageing nor improved metro access significantly affected social isolation or loneliness. Among older women, improved metro access prevented the age-related decline in social network size ($p < 0.01$) and reduced loneliness by approximately half in the treatment group compared to the control group ($p < 0.10$). It should be noted that directly comparing coefficients between men and women without accounting for baseline differences in a pooled model can be misleading due to unequal subgroup sizes. Therefore, three-way interaction models were used to test whether the observed subgroup differences were statistically significant when pooling all the participants (Appendix, Table 1A). The Time × Treatment × Gender interaction for social networks was marginally significant (Coefficient = 0.41, $p < 0.10$), lending support to the interpretation that gender moderates the impact of the metro intervention. However, no significant interaction was found for loneliness.

The observed gender differences in the effects of improved metro access on social isolation and loneliness were explored further in two ways. We first segment the older women and men in the sample based on the size of their social network (below or above average) and their

Table 1
Descriptive statistics of male participants.

	Treatment group				Control group			
	Men (N = 70)		Women (N = 116)		Men (N = 62)		Women (N = 139)	
	Baseline, Mean (SD)/%	Follow up, Mean (SD)/%	Baseline, Mean (SD)/%	Follow up, Mean (SD)/%	Baseline, Mean (SD)/%	Follow up, Mean (SD)/%	Baseline, Mean (SD)/%	Follow up, Mean (SD)/%
Social isolation factors								
Social network	12.31 (6.17)	12.41 (5.31)	13.09 (5.75)	13.37 (6.24)	11.41 (4.70)	11.24 (5.29)	13.05 (6.02)	10.97 (5.42)
Loneliness	3.98 (1.41)	3.74 (1.34)	3.61 (1.25)	3.62 (1.03)	3.5 (1.06)	3.56 (0.95)	3.53 (1.13)	3.66 (1.22)
Built environment characteristics								
Population density (in 1000 per km^2)	73.95 (29.71)	73.95 (29.71)	75.49 (33.08)	75.49 (33.08)	65.08 (26.50)	65.08 (26.50)	57.90 (25.20)	57.90 (25.20)
Density of street intersections (per km^2)	1145.64 (391.10)	1145.64 (391.10)	1184.93 (411.41)	1184.93 (411.41)	1103.03 (337.63)	1103.03 (337.63)	1168.28 (245.03)	1168.28 (245.03)
Average walkability score	53.66 (9.33)	53.66 (9.33)	52.73 (11.61)	52.73 (11.61)	62.73 (13.57)	62.73 (13.57)	61.99 (13.25)	61.99 (13.25)
Walking distance to the nearest metro station (m)	–	548.92 (256.36)	–	564.3 (312.33)	1069.51 (752.31)	1069.51 (752.31)	740.14 (563.64)	740.14 (563.64)
Destination accessibility	0.76 (0.05)	0.73 (0.08)	0.77 (0.07)	0.74 (0.07)	0.71 (0.08)	0.66 (0.10)	0.74 (0.07)	0.70 (0.08)
Individual characteristics								
Weekly public transport use time	219.35 (192.42)	242.51 (263.55)	196.26 (178.03)	244.44 (273.37)	192.48 (176.69)	177.54 (258.17)	195.23 (173.26)	165.66 (249.18)
Age	75.98 (8.08)	77.45 (8.10)	75.42 (6.91)	76.55 (6.99)	75.61 (7.46)	77.93 (6.64)	76.43 (6.47)	77.77 (6.69)
Monthly income (HKD)	4076.21 (2377.97)	4299.07 (2661.67)	4100.93 (3415.25)	4709.13 (4313.42)	4414.24 (3721.01)	4565.96 (3860.12)	4319.05 (2536.36)	4121.40 (2391.35)
Married	64.28	61.43	56.90	50.86	62.90	62.90	45.32	42.45
Middle school and below	87.14	87.14	83.92	83.92	79.03	79.03	84.89	84.89
Year of residency	27.92 (12.25)	28.93 (13.08)	24.96 (12.14)	26.94 (13.04)	24.16 (14.74)	25.54 (16.14)	20.30 (13.13)	22.77 (14.78)
Physical activity (MET/minutes)	5273.11 (3860.74)	5294.84 (3838.69)	5567.96 (3193.79)	5234.61 (3015.61)	4828.33 (3423.46)	4773.38 (2902.74)	4950.51 (3299.57)	5111.43 (3314.86)
Self-reported chronic disease	81.42	90.00	87.93	91.37	83.87	75.81	74.82	87.05
Mental health	52.65 (9.15)	49.01 (6.94)	52.62 (8.78)	50.71 (6.15)	51.89 (8.56)	49.48 (9.68)	51.78 (9.24)	50.14 (8.08)

Table 2
Results of the DID regression models for social network and loneliness.

	Social network, Coefficient (95 % CI)		Loneliness, Coefficient (95 % CI)	
	Model 1	Model 2	Model 3	Model 4
Intervention				
Time (follow-up vs. baseline)	0.04 (−0.16, 0.25)	0.03 (−0.19, 0.31)	**0.19 (-0.01, 0.40)**°	**0.25 (0.03, 0.49)***
Treatment (treatment vs. control group)	**0.25 (0.09, 0.45)****	**0.21 (0.03, 0.40)***	0.10 (−0.07, 0.26)	0.01 (−0.17, −0.17)
Time * Treatment	**0.30 (0.06, 0.53)***	**0.32 (0.06, 0.57)***	**−0.17 (-0.39, 0.05)**°	**−0.23 (-0.45, -0.01)***
Built environment characteristics	No	Yes	No	Yes
Individual covariates	No	Yes	No	Yes
Constant	0.04 (−0.10, 0.17)	**1.93 (0.21, 3.55)***	−0.10 (−0.23, 0.03)	**3.78 (2.08, 5.47)*****
R-square	0.02	0.10	0.02	0.20
N (participants)	387	387	387	387

Note: °$p < 0.10$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

loneliness level (below or above average) at the baseline survey. There are interactions between metro access improvement and social isolation and loneliness among older women. Specifically, among the least isolated ($p < 0.01$) or lonely ($p < 0.10$) older women, improved metro access has reduced and prevented increases in isolation and loneliness associated with the ageing process (Table 4). This suggests that improvements in metro access can counteract or delay reductions in social participation among older women, particularly those with a greater potential for such participation.

We also segmented the older men and women in the sample by age, income, education, and marital status (Appendix Tables 2–3). The models for social network size suggest that improved metro access can reduce or prevent increases in isolation among women aged 80 or older, those with lower education, on a low income, and married; no comparable effects are observed within the sample of older men. The results for loneliness are less straightforward, in part due to the modest number of older adults in each segment. No clear effects can be observed among older women, while metro access improvements can reduce loneliness in the treatment group to a similar level as in the control group among married older men.

3.2.3. *Robustness tests*

The results of the robustness tests are presented in Table 5. We found no statistically significant differences in measures of social isolation or loneliness between participants living near Sai Ying Pun station and those around North Point station. This finding suggests that effects on social networks and loneliness among older adults may persist over time following the metro intervention. Additionally, results remained stable when the two additional locations (Fig. 1, areas highlighted by green circles) were incorporated into the control groups. These supplementary analyses further confirm the robustness of our primary DID results.

Table 3
DID results of change in social isolation and loneliness stratified by gender.

	Social network, Coefficient (95 % CI)				Loneliness, Coefficient (95 % CI)			
	Model 5 (men)	Model 6 (men)	Model 7 (women)	Model 8 (women)	Model 9 (men)	Model 10 (men)	Model 11 (women)	Model 12 (women)
Intervention								
Time (follow-up vs. baseline)	−0.01 (−0.26, 0.26)	0.05 (−0.27, 0.36)	**−0.37 (-0.60, -0.15)***	**−0.26 (-0.50, -0.02)***	−0.07 (−0.25, 0.11)	−0.03 (−0.27, 0.21)	0.11 (−0.11, 0.32)	−0.02 (−0.24, 0.20)
Treatment (treatment vs. control group)	0.15 (−0.17, 0.48)	0.22 (−0.21, 0.6)	0.01 (−0.25, 0.26)	−0.01 (0.05, 0.54)	0.41 (0.05, 0.77)*	0.45 (−0.08, 0.82)	0.07 (−0.18, 0.32)	**0.23 (-0.04, 0.50)**°
Time * Treatment	0.02 (−0.34, 0.39)	0.09 (−0.28, 0.47)	**0.42 (0.12, 0.72)****	**0.41 (0.10, 0.72)****	−0.27 (−0.61, 0.06)	−0.31 (−0.66, 0.04)	−0.10 (−0.38, 0.18)	**−0.13 (-0.31, -0.04)**°
Built environment characteristics	No	Yes	No	Yes	No	Yes	No	Yes
Individual characteristics	No	Yes	No	Yes	No	Yes	No	Yes
Constant	−0.16 (−0.36, 0.05)	−1.41 (−4.18, 1.36)	0.12 (−0.05, 0.30)	−2.05 (−3.91, −0.18)*	0.12 (−0.35, 0.21)	3.11 (0.25, 5.96)*	0.09 (−0.25, 0.15)*	3.79 (1.79, 5.79)***
R-square	0.01	0.14	0.03	0.10	0.02	0.21	0.02	0.22
N (participants)	133	133	254	254	133	133	254	254

Note: °p < 0.10; *p < 0.05; **p < 0.01; ***p < 0.001.

Table 4
DID results stratified by baseline isolation (Above/below average groups).

	Social network, Coefficient (95 % CI)				Loneliness, Coefficient (95 % CI)			
	Men		Women		Men		Women	
	Model 13a (Below-average)	Model 13 b (Above-average)	Model 14a (Below-average)	Model 14 b (Above-average)	Model 15a (Below-average	Model 15 b (Above-average)	Model 16a (Below-average)	Model 16 b (Above-average)
Intervention								
Time (follow-up vs. baseline)	**0.39 (-0.08, 0.72)***	**−0.49 (-1.02, 0.03)**°	**0.42 (0.15, 0.69)****	**−0.90 (-1.21, 0.57)*****	0.32 (0.14, 0.49)**	−0.50 (−1.11, 0.11)	**0.43 (0.25, 0.62)*****	−0.47 (−0.92, 0.03)*
Treatment (treatment vs. control group)	−0.21 (−0.57, 0.15)	0.36 (−0.17, 0.89)	0.05 (−0.25, 0.37)	0.01 (−0.25, 0.27)	−0.05 (−0.19, 0.09)	0.61 (−0.52, 1.74)	0.08 (−0.03, 0.19)	0.29 (−0.37, 0.95)
Time * Treatment	0.23 (−0.21, 0.67)	−0.04 (−0.65, 0.58)	0.10 (−0.34, 0.53)	**0.64 (0.23, 1.05)****	−0.05 (−0.33, 0.22)	−0.14 (−0.93, 0.66)	**−0.21 (-0.45, 0.02)**°	−0.13 (−0.86, 0.61)
Built environment characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−0.45 (−2.55, 1.63)	0.74 (−2.31, 3.78)	−3.24 (−5.45, −1.03)**	−0.51 (−2.48, 1.47)	−0.83 (−2.01, 0.34)	−2.92 (−2.63, 8.48)	0.45 (−0.71, 1.62)	1.13 (−2.57, 4.82)
R-square	0.38	0.20	0.20	0.23	0.29	0.43	0.21	0.53
N (participants)	72	61	110	144	88	45	192	62

Note: °p < 0.10; *p < 0.05; **p < 0.01; ***p < 0.001.

Table 5
Robustness tests: DID regression models incorporating all groups.

	Social network, Coefficient (95 % CI)	Loneliness, Coefficient (95 % CI)
	Model 17	Model 18
Intervention		
Time (follow-up vs. baseline)	0.06 (−0.19, 0.33)	0.15 (−0.05, 0.40)
Treatment (treatment vs. control group)	0.13 (0.02, 0.30)	−0.06 (−0.22, 0.10)
Time * Treatment	**0.33 (0.09, 0.56)****	**−0.17 (-0.26, -0.07)**°
Covariates	Yes	Yes
Constant	**2.21 (0.68, 3.76)****	**3.15 (1.51, 4.80)*****
R-square	0.10	0.21
N (participants)	449	449

Note: °p < 0.10; *p < 0.05; **p < 0.01; ***p < 0.001.

4. Discussion and conclusion

Social isolation and loneliness have been critical areas of focus in gerontological research for decades. However, evidence remains limited regarding how gender intersects with public transport provision, potentially leading to heterogeneous outcomes in isolation and loneliness. This paper employs a natural experiment to identify the causal effects of a new metro line on social isolation and loneliness, explicitly differentiating between older men and women. Our findings challenge previous studies suggesting women are more susceptible to experiencing social isolation and loneliness. Instead, we found older men reported higher levels of both. The natural experiment provides compelling evidence that the new metro line does not alleviate social isolation and loneliness among older men. In contrast, older women significantly benefit from the new metro services, experiencing enhanced social networks and reduced isolation and loneliness. These benefits are particularly pronounced among women with lower initial levels of loneliness and stronger social networks prior to the intervention. By examining the intersection of gender and public transportation provision, this study advances our understanding of the gendered impact of public transport on social isolation and loneliness among older adults.

We examined the gendered effects in the context of shifting gender dynamics as older men now live longer. While recent attention has focused on the experiences of older women with public transport and social isolation, there remains a need to better understand the specific challenges that older men face, especially regarding different modes of public transport (Reinhard et al., 2018; Windle et al., 2010). Previous studies have largely emphasised women's disadvantages, often linked to their limited access to material resources (Loukaitou-Sideris, 2016). However, it is equally important to recognise the unique vulnerabilities experienced by older men. Women's lifelong engagement in gendered caregiving roles significantly shapes their overall experiences, influencing their participation in paid work and family responsibilities and, ultimately, their material circumstances in later life (Li et al., 2012). Women—particularly in Hong Kong—often cultivate and sustain their social connections through involvement in non-governmental organisations and unpaid community activities, enabling them to maintain active social lives beyond their working years. In contrast, despite men's historical advantage in labour force participation, their social networks often shrink upon retirement, leaving them particularly vulnerable to isolation. Our findings suggest that introducing new metro lines may support social participation more for older women than for men. Recognising this gender difference is essential for developing targeted policies that effectively mitigate social isolation among older men.

This study employed a natural experimental design in which treatment and control groups were comparable in context but differed in the introduction of new metro stations. We focused on older adults and examined whether enhanced public transport access affects social networks and lonelines, and whether these effects vary by gender. A difference-in-differences framework enabled estimation of intervention effects while accounting for baseline differences and time trends. A key methodological strength is the as-if random assignment of treatment and control areas, rooted in the historical planning and financing sequence of the new metro line rather than resident characteristics. This reduces selection bias and strengthens causal inference by limiting the likelihood that observed changes are driven by pre-existing socioeconomic, demographic, or health-related differences. Neighbourhood attributes and individual profiles remained relatively stable across the study period, further reinforcing internal validity.Overall, the study provides plausible causal evidence on the social isolation and loneliness impacts of public transport for older adults and highlights meaningful gender variation in response to a major infrastructure intervention.

This study has several limitations. First, natural experiment studies may encounter uncertainties, such as delays in the implementation of transport infrastructure projects. Our study experienced a lower-than-anticipated retention rate due to the two-year delay in launching the new metro line and the local outbreak of the COVID-19 pandemic. Fortunately, by the time our follow-up survey was conducted, Hong Kong had been free of community cases for seven months, likely minimising the pandemic's influence on the travel habits of the older population. Second, public transport usage behaviours were collected through a self-reported questionnaire, which allowed us to access a large cohort but may have introduced some recall bias. To mitigate this, our survey was administered by trained interviewers to enhance the credibility of participants' responses. Third, caution is needed when generalising our findings to other contexts due to the public transport dependence and the high-density urban environment in Hong Kong. However, our research design should be transferable and could be adapted for transport and healthy ageing studies in other regions. Finally, due to the nature of a natural experiment, conducting multiple baseline surveys is often infeasible, as the timing and implementation of interventions are beyond the control of researchers. Nevertheless, a longitudinal survey with multiple follow-up waves could help verify the robustness of changes in health outcomes. This, however, would depend on the availability of funding and the participants' retention rate.

Despite the limitations, our research has two unique strengths. First, we examined how public transport affects social isolation and loneliness among older adults in high-density Asian cities, with an emphasis on gender differences. Unlike previous studies focused primarily on buses or light rail, our research specifically investigates metro interventions. Hong Kong is an ideal case study, as its metro system forms the backbone of public transport, and active ageing has become a policy priority. Metro systems involve fixed infrastructure that is costly and complex to modify once built, unlike bus routes that can be easily adjusted based on demand (Sun et al., 2020; Sun and Zacharias, 2017). Moreover, the Hong Kong government often allows for restructuring or reducing bus services following metro expansion, thereby reinforcing the metro's role as the primary transport mode. Consequently, metro infrastructure investments could have profound, long-lasting impacts on urban mobility, significantly reshaping travel behaviours and influencing social isolation and loneliness among older adults who previously relied on buses (Du et al., 2022b). Second, we leveraged local transport planning knowledge to justify our assignment of treatment and control groups, enhancing the robustness of our comparisons regarding changes in social isolation and loneliness. Situational factors remained stable across groups, with differences primarily arising from the timing of transit provision, which was influenced by financial and planning constraints. This supports a valid counterfactual estimation (de Vocht et al., 2021; Sun et al., 2023). By employing a natural experiment design, we can effectively minimise potential confounding factors, ensuring transparency in our analysis and the reliability of our results.

The findings have some policy implications. Addressing isolation and loneliness requires concerted action from individuals, organisations, and the government (Loukaitou-Sideris, 2016; Neville et al., 2018). Support services should be specifically designed with the interests and needs of older men. While there has been a growth in specific interventions aimed at tackling social isolation and loneliness in recent years, it is important to note that most activities for older people are still gender-neutral, not explicitly targeting men or women. Anecdotal evidence suggests that women tend to use these services disproportionately, leaving a gap in addressing the needs of older men (Beach and Bamford, 2014). Policymakers could have a more comprehensive understanding of how gender influences travel patterns, social interactions, and experiences of loneliness among older men. Transport planning and health practitioners should be sensitive to gender and other characteristics of disadvantage in later life, ensuring that interventions and initiatives effectively address the specific needs and challenges older men face.

In conclusion, this paper provided plausible causal evidence on the varied health and wellbeing impacts of mobility using the metro on different genders within the older population. Our findings suggest targeting differential gender and age groups to inform the development of more precise transport services, health practices, and infrastructure programs that cater to the specific needs and challenges of these groups in active mobility. While our research specifically examined Hong Kong, the observed gendered patterns in transport-related isolation and loneliness hold valuable insights transferable to other densely populated Asian cities such as Tokyo, Seoul, or Singapore, which share similar ageing trends, cultural expectations, and transportation infrastructures.

CRediT authorship contribution statement

Guibo Sun: Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Writing – original draft. **Yao Du:** Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – review & editing. **Tim Schwanen:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – review & editing.

Appendix

Table 1A
DID results of change in social isolation and loneliness moderated by gender

	Social network, Coefficient (95 % CI)		Loneliness, Coefficient (95 % CI)	
	Model 1	Model 2	Model 3	Model 4
Intervention				
Time (follow-up vs. baseline)	−0.01 (−0.26, 0.25)	0.17 (−0.11, 0.45)	0.07 (−0.15, 0.29)	−0.20 (−0.44, 0.04)
Treatment (treatment vs. control group)	0.15 (−0.17, 0.48)	0.15 (−0.19, 0.50)	0.41 (0.05, 0.77)*	0.48 (0.13, 0.82)*
Gender	0.28 (0.02, 0.55)*	0.26 (−0.02, 0.53)°	0.03 (−0.25, 0.30)	0.06 (−0.18, 0.31)
Time * Treatment	0.02 (−0.35, 0.39)	0.01 (−0.36, 0.38)	−0.28 (−0.61, 0.06)	−0.25 (−0.59, 0.09)
Time * Gender	−0.37 (−0.71, −0.03)*	−0.40 (−0.74, −0.06)*	0.03 (−0.28, 0.34)	0.07 (−0.23, 0.36)
Treatment * Gender	−0.15 (−0.55, 0.26)	−0.14 (−0.55, 0.27)	−0.34 (−0.78, 0.10)	−0.33 (−0.73, 0.07)
Time*Treatment*Gender	**0.40 (-0.07, 0.87)**°	**0.41 (-0.07, 0.89)**°	0.18 (−0.26, 0.61)	0.18 (−0.24, 0.61)
Built environment characteristics	No	Yes	No	Yes
Individual characteristics	No	Yes	No	Yes
Constant	−0.16 (−0.36, 0.04)	−2.30 (−3.84, −0.75)	0.12 (−0.05, 0.30)	−2.05 (−3.91, −0.18)*
R-square	0.03	0.08	0.03	0.18
N (participants)	387	387	387	387

Note: °p < 0.10; *p < 0.05; **p < 0.01; ***p < 0.001.

Table 2A
DID results of change in social network stratified by sociodemographic subgroups (age, income, education, marriage status, etc.)

	Men: Social network, Coefficient (95 % CI)							
	Model 9a (65–80)	Model 9 b (80 and above)	Model 10a (monthly income <3200)	Model 10 b (monthly income ≥3200)	Model 11a (Middle school and below)	Model 11 b (high school and above)	Model 12a (married)	Model 12 b (single, divorced and widowed)
Intervention								
Time (follow-up vs. baseline)	−0.05 (−0.51, 0.42)	0.38 (−0.05, 0.80)°	−0.36 (−1.08, 0.36)	0.21 (−0.12, 0.55)	0.06 (−0.32, 0.44)	0.33 (−0.52, 1.19)	−0.10 (−0.49, 0.29)	0.09 (−0.48, 0.67)
Treatment (treatment vs. control group)	−0.05 (−0.52, 0.42)	0.74 (−0.01, 1.49)°	0.19 (−0.75, 1.14)	0.13 (−0.35, 0.62)	0.24 (−0.21, 0.69)	0.41 (−1.24, 2.05)°	0.65 (0.14, 1.15)*	−0.20 (−0.92, 0.51)*
Time * Treatment	0.27 (−0.25, 0.78)	−0.14 (−0.79, 0.50)	0.08 (−0.78, 0.94)	0.18 (−0.24, −0.61)	0.09 (−0.35, 0.53)	−0.22 (−0.56, 0.99)	0.13 (−0.37, 0.63)	0.26 (−0.39, 0.93)
Built environment characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−2.49 (−5.93, 0.94)	−2.40 (−6.10, 1.29)	−1.09 (−6.59, 4.39)	−0.93 (−4.11, 2.26)	−1.26 (−4.16, 1.63)	−1.07 (−10.64, 8.49)	1.19 (−2.09, 4.41)	−2.79 (−6.64, 1.05)
R-square	0.25	0.16	0.24	0.18	0.14	0.42	0.23	0.31
N (participants)	68	65	41	92	113	20	82	51

Note: °p < 0.10; *p < 0.05; **p < 0.01; ***p < 0.001.

Table 2B
DID results of change in social network stratified by sociodemographic subgroups (age, income, education, marriage status, etc.)

	Women: Social network, Coefficient (95 % CI)							
	Model 3a (65–80)	Model 13 b (80 and above)	Model 14a (monthly income <3200)	Model 14 b (monthly income ≥3200)	Model 15a (Middle school and below)	Model 15 b (high school and above)	Model 16a (married)	Model 16 b (single, divorced and widowed)
Intervention								
Time (follow-up vs. baseline)	−0.15 (−0.49, 0.17)	**−0.46 (-0.82, -0.10)***	−0.61 (−1.02, 0.21)	−0.13 (−0.42, 0.15)	**−0.29 (-0.55, -0.04)***	0.08 (−0.69, 0.87)	−0.41 (−0.75, 0.06)	−0.14 (−0.47, 0.18)
Treatment (treatment vs. control group)	0.11 (−0.23, 0.46)	−0.27 (−0.78, 0.25)	0.08 (−0.37, 0.53)	−0.03 (−0.40, 0.35)	−0.05 (−0.38, 0.27)	0.72 (−0.11, 1.54)	0.12 (−0.28, 0.53)	−0.06 (−0.49, 0.36)
Time * Treatment	0.14 (−0.27, 0.55)	**1.09 (0.55, 1.63)*****	**0.66 (0.13, 1.18)***	0.37 (−0.01, −0.75)°	**0.46 (0.13, 0.79)****	0.10 (−0.92, 1.13)	**0.47 (0.02, 0.93)***	0.42 (−0.05, 0.89)°
Built environment characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

(*continued on next page*)

Table 2B (*continued*)

	Women: Social network, Coefficient (95 % CI)							
	Model 3a (65–80)	Model 13 b (80 and above)	Model 14a (monthly income <3200)	Model 14 b (monthly income ≥3200)	Model 15a (Middle school and below)	Model 15 b (high school and above)	Model 16a (married)	Model 16 b (single, divorced and widowed)
Constant	−2.99 (−4.70, 1.28)	−0.17 (−3.13, 2.80)	−3.41 (−6.78, −0.03)*	−1.45 (−3.56, 0.65)	−1.95 (−3.97, 0.07)°	−4.20 (−10.15, 1.74)	−0.32 (−3.17, 2.52)	−2.95 (−5.21, −0.69)*
R-square	0.09	0.18	0.29	0.07	0.08	0.27	0.09	0.13
N (participants)	161	93	78	176	215	39	118	136

Note: °p < 0.10; *p < 0.05; **p < 0.01; ***p < 0.001.

Table 3A
DID results of change in social network stratified by sociodemographic subgroups (age, income, education, marriage status, etc.)

	Men: Loneliness, Coefficient (95 % CI)							
	Model 17a (65–80)	Model 17 b (80 and above)	Model 18a (monthly income <3200)	Model 18 b (monthly income ≥3200)	Model 19a (Middle school and below)	Model 19 b (high school and above)	Model 20a (married)	Model 20 b (single, divorced and widowed)
Intervention								
Time (follow-up vs. baseline)	0.01 (−0.33, 0.34)	−0.15 (−0.59, 0.28)°	−0.24 (−0.86, 0.38)	−0.04 (−0.34, 0.25)	−0.10 (−0.37, 0.16)	−0.33 (−1.08, 0.42)	−0.12 (−0.44, 0.18)	−0.24 (−0.67, 0.18)
Treatment (treatment vs. control group)	0.41 (−0.04, 0.86)°	0.68 (−0.05, 1.41)°	0.32 (−0.58, 1.22)	**0.56 (-0.09, 1.04)***	0.54 (0.15, 0.94)**	−0.38 (−1.50, 0.74)°	**0.42 (0.06, 0.78)***	0.60 (−0.21, 1.41)
Time * Treatment	−0.22 (−0.79, 0.36)	−0.32 (−0.96, 0.31)	−0.26 (−1.12, 0.59)	−0.33 (−0.71, −0.04)°	−0.29 (−0.68, 0.09)	0.25 (−0.56, 1.06)	**−0.39 (-0.79, -0.01)***	0.05 (−0.63, 0.74)
Built environment characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	1.68 (−2.83, 6.21)	3.36 (−0.66, 7.38)	0.32 (−7.06, 7.72)	3.97 (1.17, 6.77)	3.82 (0.86, 6.78)*	−3.05 (−11.64, 5.54)	0.68 (−3.59, 4.97)	7.49 (3.37, 11.61)***
R-square	0.21	0.22	0.23	0.28	0.21	0.37	0.18	0.40
N (participants)	68	65	41	92	113	20	82	51

Note: °p < 0.10; *p < 0.05; **p < 0.01; ***p < 0.001.

Table 3B
DID results of change in social network stratified by sociodemographic subgroups (age, income, education, marriage status, etc.)

	Women: Loneliness, Coefficient (95 % CI)							
	Model 21a (65–80)	Model 21 b (80 and above)	Model 22a (monthly income <3200)	Model 22 b (monthly income ≥3200)	Model 23a (Middle school and below)	Model 23 b (high school and above)	Model 24a (married)	Model 24 b (single, divorced and widowed)
Intervention								
Time (follow-up vs. baseline)	−0.05 (−0.36, 0.25)	−0.01 (−0.35, 0.34)	−0.08 (−0.42, 0.26)	−0.02 (−0.28, 0.25)	0.05 (−0.18, −0.28)	−0.52 (−0.98, −0.05)*	0.06 (−0.24, 0.37)	−0.09 (−0.41, 0.23)
Treatment (treatment vs. control group)	0.24 (−0.07, 0.55)	0.12 (−0.42, 0.66)	0.01 (−0.44, 0.45)	0.03 (−0.05, 0.58)	0.33 (0.04, 0.62)*	−0.09 (−0.74, 0.55)	0.03 (−0.29, 0.36)	0.34 (−0.05, 0.74)
Time * Treatment	−0.14 (−0.49, 0.22)	0.01 (−0.53, 0.54)	−0.03 (−0.47, 0.41)	−0.14 (−0.48, 0.21)	−0.26 (−0.55, 0.03)°	0.49 (−0.18, 1.18)	−0.16 (−0.56, 0.23)	−0.09 (−0.52, 0.33)
Built environment characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	3.59 (1.75, 5.43)***	3.26 (0.32, 6.22)*	3.01 (−1.03, 7.03)	3.97 (1.77, 6.17)***	3.72 (1.58, 5.86)***	4.47 (−1.35, 10.31)	0.98 (−1.71, 3.67)	4.86 (2.20, 7.53)***
R-square	0.24	0.19	0.26	0.23	0.23	0.41	0.11	0.28
N (participants)	161	93	78	176	215	39	118	136

Note: °p < 0.10; *p < 0.05; **p < 0.01; ***p < 0.001.

Data availability

The authors do not have permission to share data.

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