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Do pedestrian safety improvements affect older adults' health and social outcomes equitably? A quasi experiment in Singapore

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Do pedestrian safety improvements affect older adults' health and social outcomes equitably? A quasi experiment in Singapore

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A B S T R A C T

Introduction: Pedestrian-friendly neighborhoods are believed to encourage greater social participation, community engagement, and sense of social inclusion, which are important to older individuals at higher risk of being socially isolated. However, most studies on neighborhood walkability, social participation and social inclusion are cross-sectional, making it difficult to robustly establish causal links. Much research on neighborhood walkability is also based in North America and Europe, leaving a knowledge gap on the impact of walkability within other geographic contexts. Furthermore, there is a lack of empirical evidence about whether benefits from traffic calming schemes are distributed equitably. To reduce these empirical gaps, our study capitalises on a 'quasi-experiment' to estimate the impact of an infrastructure-focused pedestrian safety program "Silver Zones' in Singapore, a highly urbanised city state in Southeast Asia with an aging population.

Methods: This study utilises panel data from a high-frequency internet-based survey of older adults that has been administered from 2015 till present. We examine how changes in older residents' residential proximity to Silver Zones relate to changes in their social and health outcomes. We also test whether the relationship between Silver Zones and older individuals' health and social participation outcomes might be moderated by age and socioeconomic class. Finally, we interpret these findings in view of participants' perceptions of Silver Zones.

Results and conclusion: We find that the oldest participants with low SES – a particularly vulnerable subgroup – experienced negative changes after the opening of Silver Zones near them, as did those classified as mid SES. In contrast, our findings suggest that new Silver Zones might have a positive effect on older adults of high SES. These findings suggest that there might be inequities in the impact of pedestrian safety programs on residents' social outcomes. Additionally, while our findings were statistically significant, they also suggest that Silver Zones' contribution to changes in participant outcomes were relatively small, which might be due to a mismatch between perceptions of Silver Zones, actual exposure, and participant outcomes. Our findings underscore the need for more outreach and publicity campaigns around pedestrian safety initiatives, as well as the importance of going beyond self-reported perceptions when assessing the success of pedestrian safety schemes like the Silver Zones.

1. Introduction

Life expectancies world-wide have been increasing, yet the increased years of life are often encumbered by poor health. As populations age, policy-makers all over the world have to grapple with various social and health risks older adults face, in order to provide environments supportive of healthy ageing (Beard et al., 2016). One such risk that older adults face is that of being socially isolated, in part because they are more likely to face mobility challenges. Older adults also face increased risks of injuries, including traffic-related ones, and falls than younger adults (Lin and Cui, 2021; Y. Wang et al., 2017). Restricted mobility and fears of injuries, whether from neighborhood traffic or challenging pedestrian conditions, affect their ability to leave their homes and engage in social activities that provide social interactions within their community or society—social participation in other words (Levasseur et al., 2015, 2022). Social isolation is problematic because it is associated with many negative health and well-being effects (Courtin and Knapp, 2017;

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Nicholson, 2012). On the flip side, studies suggest that greater social participation among older adults might combat loneliness (Niedzwiedz et al., 2016), reduce risk of mortality (Smith et al., 2018), support cognitive functioning (Kelly et al., 2017), and generate greater satisfaction with life (Levasseur et al., 2010) amongst other positive outcomes (Levasseur et al., 2015, 2022).

Modifying the neighborhoods of older adults to be more pedestrian-friendly presents an important opportunity to support social participation. This is because older adults tend to have more limited range of mobility and stronger place-attachment to their neighborhoods, and thus spend more time in their immediate neighborhood than younger adults (Bonaccorsi et al., 2023; Levasseur et al., 2015). Creating pedestrian-friendly neighborhoods can be achieved through improving pedestrian infrastructure, such as widening sidewalks, reducing vehicle speed limits, and installing safe intersections and signalised pedestrian crossings (Scharlach and Lehning, 2013). Such improvements reduce the risks of traffic injuries or falls, remove physical barriers to walking around the neighborhood, and thus encourage more walking. For instance, a 2018 survey of over 1000 older adults in Singapore found evidence that the presence of more unsignalised, and thus less safe, pedestrian crossings near participants' residences was associated with reduced daily walking travel (Hou et al., 2020).

In short, walkable, pedestrian-friendly neighborhoods support older people feeling safer leaving the house to participate in social activities, or even to walk around exploring their neighborhood amenities (Levasseur et al., 2015; Padeiro et al., 2022). Through such activities, residents also have more opportunities to have chance encounters with their neighbors; and build relationships around the neighborhood. These behavioural changes towards greater social participation would in turn support better physical and mental health outcomes (du Toit et al., 2007; Hassen and Kaufman, 2016; Leyden, 2003), as described earlier.

Understanding which built environment changes might have a positive impact on older adults' mobility and social participation is thus urgently needed, especially in Asian societies facing a rapidly aging population. Researchers have sought to prove this theorized link between neighborhood walkability, social interaction and social inclusion (Matsumoto et al., 2022). For instance, a 2003 study comparing the citizens living in more pedestrian-oriented neighborhoods versus those living in more suburban, car-dependent ones in Galway, Ireland found that the former had higher levels of social capital, were more likely to know their neighbors; participate politically; trust others, and be socially engaged (Leyden, 2003). However, this study, as with most such studies looking at place effects on health and well-being, was cross-sectional in nature—focusing only on a single timepoint of exposure to walkable neighbourhoods and outcomes. Using such static, cross-sectional analyses makes it difficult to robustly establish causal links between place and social outcomes (Arcaya et al., 2016; Hassen and Kaufman, 2016). There is thus a need for studies employing causal inference methods that can more robustly unpack the effect of pedestrian environments. However, studying built environmental effects causally can be very challenging as it is both unethical and logistically difficult to conduct randomised controlled trials of built environment interventions. As an alternative, researchers could instead rely on 'natural experiments' or 'quasi-experiments' to test if exogenously generated changes to a neighborhood pedestrian environment might translate into changes in individual outcomes (Sun et al., 2023). Natural experiments are where the treatment varies through some 'naturally' occurring event exogenous to the outcome, whereas for quasi-experiments, treatments might be designed to influence outcomes of interest, and lack full random assignment (Remler and Van Ryzin, 2014).

Traffic calming programs present a valuable opportunity to do precisely this. Traffic calming refers to road design strategies to reduce vehicle speeds and volumes, including setting speed limits, raising crosswalks, adding speed humps or traffic circles, pavement treatments and other measures (Litman, 1999). Traffic calming measures render a neighborhood safer to walk around in and thus more pedestrian-friendly, which as discussed earlier, can encourage greater social participation of older adults.

There have been a few empirical studies quantifying the impact of traffic calming schemes on pedestrian activity and health. For example a 2004 study surveyed 185 residents of an urban neighborhood in Glasgow, Scotland, six months before and after a traffic calming scheme, which involved the installation of speed cushions, zebra crossings and parking bays, was implemented in their neighborhood. Researchers found increases in observed pedestrian activity in the area; and improvement in self-reported physical health but not mental health (Morrison, 2004). Similarly, several studies of 20 mph zones in the UK found that lower speed limits, speed bumps, road narrowing, mini-roundabouts and other improvements implemented to slow traffic and improve safety effectively reduced traffic-related injuries, improved perceptions of safety, and to a lesser extent affected physical activity (Cairns et al., 2015; Cleland et al., 2020; Pilkington et al., 2018). However, by and large, despite the popularity of traffic calming interventions, there have been only a few studies, such as the Glasgow study by Morrison (2004) described above, that explicitly take advantage of the 'natural experimental conditions' offered by such interventions. Instead most studies looking at the relationship between road conditions and health tend to be cross-sectional and thus can only observe non-causal associations (Brown et al., 2017). Moreover, none that we are aware of has explicitly examined their impact on social participation.

Another important consideration is how the impact of pedestrian environments' on older adults might differ by relative age and income. For instance, empirical studies have shown a positive association between pedestrian age and severity of traffic injuries (Y. Wang et al., 2017). Studies also suggest that poorer adults are at higher risks of traffic-related injuries than wealthier counterparts (Rodgers et al., 2010). Given these differences in susceptibility to traffic-related accidents, we can reasonably hypothesize that older adults' responses to traffic calming measures might differ by relative age and income. For instance, one might hypothesise that those who are more vulnerable to traffic-related injuries (i.e. the oldest old who are low-income) might benefit more from traffic-calming improvements as these improvements might help them feel safer in their neighborhoods, whereas their less vulnerable counterparts who do not require these protective improvements as much might be less affected. Benefiting the more vulnerable groups would be an instance of 'vertical equity', which refers to "the distribution of impacts between people or groups that differ in wealth and ability, with the assumption that people who are disadvantaged may require greater public resources" (Litman 1999).

Scholars have in fact hypothesised that traffic calming schemes could help improve 'vertical equity' (Litman 1999; Brown et al., 2017) because they are designed to benefit pedestrians and cyclists more than drivers, and because the former are more likely to be physically, economically and socially disadvantaged than the latter group. However, as far as we are aware, there are currently no published research studies documenting differentiated responses to traffic calming schemes by age or socioeconomic status, rendering it impossible to verify the likely impact of traffic calming schemes on equity.

The majority of studies looking at built environments and how they affect human health and well-being, including the various studies specific to walkability as well those focused on older adults cited in this paper thus far, tend to be situated in North America, Europe, Australia and New Zealand (Barnett et al., 2017; McGrath et al., 2015; H. Wang and Yang, 2019). It is thus challenging to generalise insights from the existing literature to populations living in other less-studied regions. In particular, many Asian societies are currently grappling with the challenges of rapidly aging populations (Balachandran et al., 2020). Cities in these countries have significant differences from typically studied Western cities in terms of built environment characteristics, such as much higher built densities, more mixing of land uses and good provision of public transportation (Cerin et al., 2011; Chen et al., 2020), which likely translates into differences in both walking and driving behaviors, as well as risks of pedestrian injuries (Sung et al., 2022). As there are potentially differences in the ways neighborhood environments affect social participation amongst older adults between the West and East, results from Western settings might not seamlessly apply to Asian contexts. More research on the links between walkability and older adults' well-being and health in Asian cities is thus critically needed.

To plug this empirical gap, this study looks at a policy-driven 'quasi-experiment' in Singapore, a high-density city state in Southeast Asia. Like many of its Asia Pacific counterparts, such as Japan, South Korea, Hong Kong, Thailand, Macao and China, Singapore is set to have one of the region's highest ratio of adults 65 years and older, compared to economically active individuals aged 15 to 64 by year 2050 (OECD & WHO, 2020). Faced with a rapidly aging population, Singapore has in recent years rolled out initiatives to ensure its built environment can facilitate healthy ageing (Tao et al., 2021). One of these initiatives is an infrastructure-focused road safety improvement program (Silver Zones). This study compares social participation outcomes of older residents before and after the implementation of Silver Zones in their neighborhoods. We also examine how these outcomes may differ by age and socioeconomic status.

The main research question guiding this study is: "Do Silver Zones increase social participation and social satisfaction, as well as improve general health, among older residents living nearby?" Our hypothesis is that older residents will report increased levels of social participation, satisfaction, as well as improvements in general health, after experiencing increased spatial access via a Silver Zone.

The second research question this study examines is: "Does age or socioeconomic status (SES) moderate the relationships between Silver Zone access and participant outcomes, in terms of social participation, satisfaction, and general health?" Given the lack of work on this particular topic, we did not have specific predictions about these moderating effects.

From this analysis, we seek to generate insights about the relationship between pedestrian walkability and social participation among older adults, within an urban context that is high-density, mixed in terms of land use, and has an extensive public transportation system— that therefore might be applicable to other Asia Pacific cities with similar environmental qualities and an aging population.

2. Methods

2.1. Overview of Silver Zones

In 2014, Singapore's land transport authority (LTA) introduced the Silver Zones scheme, which involves the implementation of

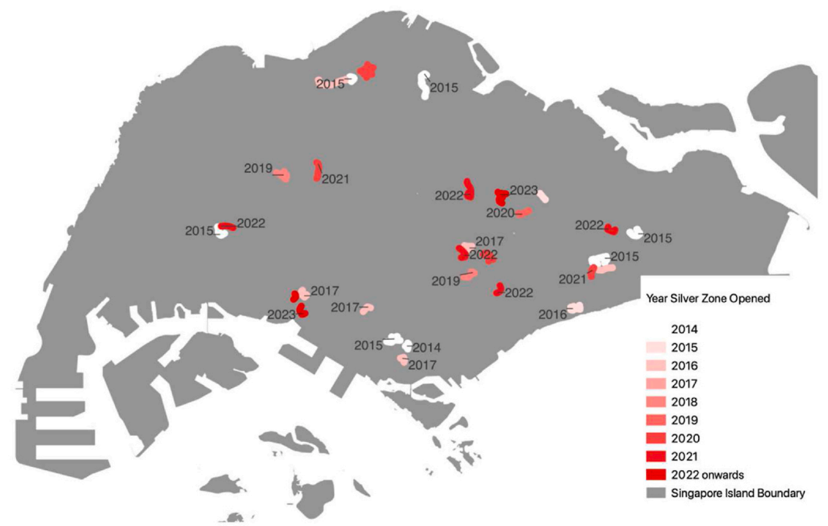

Fig. 1. Location of silver zones and opening years.

"traffic-calming measures and senior-friendly road safety features at areas with a high proportion of senior residents, and where there have been past accidents involving seniors." (LTA, 2020) The types of improvements implemented as part of the scheme include road redesigns that slow traffic, as well as ample signage signaling speed limits (40 km per hour, or roughly 25 miles per hour). The LTA has reported that the accident rate for senior pedestrians within completed Silver Zones has been reduced by approximately 80% since 2014 (LTA, 2020). While no further details about the specifics of this assessment is available, as a point of reference there were 194 accidents involving older pedestrians in 2014 in Singapore as a whole (Singapore Police Force, 2015), which increased to 235 in 2022 (Singapore Police Force, 2022). This suggests that the reported 80% reduction in accident rates for senior pedestrians within Silver Zones was not part of a general improvement throughout Singapore, but rather reflects a program-specific effect.

Fig. 1 shows where these Silver Zones are implemented in Singapore between 2014 and 2023. LTA has committed to implementing 50 Silver Zones by the end of 2025.

2.2. Data source

This study utilises data from the Singapore Life Panel (SLP), a high-frequency internet-based survey where respondents answer monthly surveys via a secure internet portal. Eligible respondents were Singaporeans (citizens and permanent residents) ages 50–70 years at the point of recruitment in 2015, and their spouses. The choice of fairly wide age range was intended to facilitate the identification of differences between the "young" old and the "older" old. In total, 11,500 households were recruited in 2015. Following a sample refresh in 2022, an additional 1724 households were added to the SLP. After accounting for attrition and the removal of non-active panel members, the panel now stands at 10,104. Every month, respondents are invited to participate in a short survey covering spending, income, labour market status, health, and life satisfaction, while additional questions were fielded at quarterly intervals. Additional one-off topical modules are also administered periodically. Since 2015, the SLP has maintained a response rate of above 70% each month. Details of the SLP methodology have been published in Vaithianathan et al. (2018).

2.3. Outcome variables

This study focuses on three repeated measures of social participation and satisfaction, and one measure of general health. The first variable measured how frequently participants left their home. Participants were asked the following question "Over the last month, how often did you leave the house, flat or apartment in which you live?" and were provided with five answer options ranging from 'Never' to "Daily'. The second outcome variable measured participants' frequency of taking part in a series of five different activities: visiting friends or family; participating in religious activities; group activities; physical activities; and hobbies. Like the first outcome, participants chose from a range of five answer options from 'Never' to 'Daily'. This study focuses on the aggregated average response to the five questions. For these two measures, data collection started from 2018 onwards.

The third outcome variable measured participant's overall satisfaction with their social life. Participants were asked "How satisfied are you with your social contacts and family life?" and were given five answer options ranging from 'Very satisfied' to 'Very dissatisfied'. The fourth outcome is a measure of general health: "Would you say your health is excellent, very good, good, fair, or poor? For the third and fourth measures, data was collected from 2015 onwards.

All variables are coded from 1 to 5.1 indicates lowest levels of social participation, social satisfaction, and good health, and 5 indicates the highest levels of these outcomes. As the SLP is a high frequency survey where data are collected from each respondent as frequently as once a month, we took the yearly average of each outcome.

2.4. Treatment variables

The primary treatment variable of interest is the shortest distance (unit = meters) between participants' homes and the boundary of the nearest Silver Zone. Here, participants' addresses were geomasked, to protect the anonymity of respondents. Geomasking was done by randomly selecting a substitute postal code from a list of six other buildings located close to the participants' original addresses —a technique also known as "Verified Neighbor Masking" (Richter, 2018).

The study sample consists of only participants living within 1 km (km) of a Silver Zone. When trying to isolate the potential impact of increased access to Silver Zones, it is important to consider if there might be other major differences between Silver Zone neighborhoods and other neighborhoods further away from Silver Zones, which could introduce bias. Comparing neighborhood characteristics of residential buildings within 400m of Silver Zones implemented as of end 2021 with those located between 400m and 1 km away, and with those further than 1 km, we find that residential buildings within 400m of at least 1 Silver Zone (n = 3137) differed in various ways from those that were farther away. This included greater access to bus stops and bus services, food outlets generally, convenience stores, supermarkets/markets, recreational spaces, and park connectors. Residential prices were also likely to be lower in the areas further from Silver Zones (see Appendix B for comparison).

These differences were larger for buildings located beyond 1 km of a Silver Zone than those within 400- 1 km. For that reason, this study focuses on residents living within 1 km of a Silver Zone as of 2020, on the basis that those living relatively closer are likely to provide a better 'control' group for comparison than those living much further away, who may be experiencing a substantially different built environment.

One might argue that another possible source of confounding is that the opening of Silver Zones might coincide with other changes in the built environment. If so, the relationship we might observe between increased access to Silver Zones and changes in social outcomes might be driven by these other neighborhood changes, rather than changes in Silver Zone access per se. As a check, we examined the correlation between changes in access to Silver Zones and changes in other built environment characteristics that took place between 2015 and 2021 (**see** Appendix A**).** By and large, we found relatively low levels of correlation, which suggests that other changes in neighborhood environment were unlikely to be confounding our analysis of Silver Zones.

2.5. Moderating variables

To test whether age and SES moderated the relationship between Silver Zone access and the various outcome measures, categorical variables of age and SES were generated from the baseline data collected when participants first joined the SLP.

Three age categories were defined based on the baseline age of participants. Those who were 50–59 at point of joining the SLP were classified as 'Youngest', those 60 to 64 were 'Middle', while those 65 and over were classified as 'Oldest'. In our analysis we included relatively young participants in order to compare whether we see differences in relationships compared to older participants.

Participant SES was defined as 'low', 'mid' and 'high' based roughly on participants' tertile distribution of self-reported monthly household income, which include non-work income from friends, family, retirement plans and other sources. Participants who report monthly incomes as of 2015 of under 1600 Singapore Dollars (SGD), or around 1165 U.S Dollars, were classified as having 'Low SES', those reporting 1600 to 3900 SGD, or around 1165 to 2840 U.S Dollars, were classified as having 'Mid SES', while those reporting more than 3900 SGD were classified as having 'High SES'. If participants' first recorded monthly incomes were collected after 2015, the tertile cut-offs were adjusted by applying a year-specific adjustment that corresponded to the relative increase in national median household income, using 2015 as a base. For instance, the adjustment factor was 1.07 for 2018, 1.04 for 2017, and 1.02 for 2016 (Singapore Department of Statistics, 2023).

2.6. Sample population

The study sample consists of participants who participated in the first wave of the SLP and then again from 2017 onwards, to ensure that there are at least two data points to track changes over time, and that these data points cover a sufficiently long period after the introduction of the Silver Zone program.

The study's sample also focused on non-movers, which are participants who did not change residential locations throughout participation in the SLP. Changing residential locations often coincides with major life changes, such as changes in occupational status, changes in family structure or marital status, which might again complicate analysis. Importantly, residential relocation coincides with locational preferences. For instance, participants may proactively move to a Silver Zone area because they value the amenities offered. If so, the 'effect' of an increase in Silver Zone access might be confounded by participants' locational preferences. In contrast, by focusing on those who did not move during the study period, we can more confidently assume that the increase in Silver Zone access is an 'exogenous', policy-driven change, which allows us to better isolate the effect of building new Silver Zones on residents. Furthermore, in April 2020, Singapore entered a pseudo lock-down period due to the COVID-19 pandemic, in which social activities were heavily curtailed. To avoid bias, we excluded responses collected from April 2020 onwards from this study.

To maximise the number of responses for analysis, we did not further restrict the sample set to only participants who responded to survey questions for all four outcomes of interest. As a result, the four models are estimated using slightly differing sample groups, with larger samples for the outcomes 'social satisfaction' and 'general health', which had been collected over a longer period than the outcomes 'frequency of leaving home' and 'social participation'. Nevertheless, as the sample populations share almost identical distributions by gender, ethnicity, educational attainment, marital status, age and SES categories, we assume the groups are more or less comparable. In total, the total sample across all four models consisted of 3213 unique participants.

2.7. Analytical approach

2.7.1. Statistical analysis

The 'predictor' variable of interest is spatial access to a Silver Zone, operationalized as the distance between a participant's home address to the nearest Silver Zone. The opening of a new Silver Zone close to one's home would lead to a shorter distance between one's home and Silver Zone, and thus greater Silver Zone access.

To analyse the relationship between spatial access to Silver Zones and participant outcomes, we specified models with individual-level fixed effects, where effect estimates are based solely on within-person variation. Effectively, modelling within-individual variation allows each individual to act as their own control, precluding the need for comparison against an external 'control group', while accounting for both observable and unobservable unit-specific characteristics (Allison, 2009; Gunasekara et al., 2014). In other words, including individual fixed effects produces estimates that are thus arguably robust to individual-level, time-invariant confounders such as gender, race/ethnicity, stable personality traits and behaviors, amongst others. Additionally, year fixed effects are also included, to control for changes over time that might be affecting all individuals. While the use of fixed effects has its share of critics, such an approach is common in economics, political science and other social science disciplines, and is often considered a 'default' method of analysing panel data (Bell and Jones, 2015).

We fitted four model specifications. First was a base model with the predictor variable only. Second and third models included interactions by baseline age categories and interactions by baseline SES categories respectively. As a robustness check, we fitted models with two age and SES categories (i.e. 'Older', 'Younger' and 'Lower SES' and 'Higher SES') instead of three.

To preclude the possibility that there might be confounding by SES or age for models two and three, as well as to test the possibility that SES and age work interactively, we tested a fourth model with interactions by a combination of age and SES categories. As testing either three-way interactions between Silver Zone access, age and SES, or testing all possible combinations of age and SES categories would result in an unwieldy model that is hard to interpret, we decided to simplify the possible combinations into four categories: Low SES & Oldest; Low SES & Younger; Higher SES & Oldest; Higher SES & Younger. Here, 'Younger' refers to participants who were classified as either 'Mid' or 'Youngest' while 'Higher SES' refers to those classified as either Mid SES or High SES. Throughout our analyses, we focus on 'low SES' and 'oldest' categories as the key reference categories, in order to concentrate on the experiences of the more socially vulnerable subpopulations.

For all models, we also included two lagged variables that tested for possible 'delayed effects' one and two years after the completion of a new Silver Zone.

To verify whether modelling for individual fixed-effects is more appropriate than using individual random-effects, we conducted Hausman tests, with a null hypothesis of the random-effects model being the preferred model. We report the chi-square test statistics from this assessment, as well as F-test and 'within' subjects' R-squared test statistics in the regression results tables.

All analyses were conducted in R, version 4.1.3. Fixed effects models were fitted using the 'plm' package, version 2.6-1.

2.8. Descriptive analyses of Silver Zone perceptions

In May 2023, SLP participants were further surveyed about their perceptions of Silver Zones near their homes (See Appendix C for questions). Respondents who indicated they were aware of Silver Zone near their homes were queried about whether they felt the Silver Zone positively or negatively affected them, and if so why. Simple descriptive statistics, such as frequency tabulations, were used to examine common perceptions of Silver Zones. We also conducted t-tests to examine whether these perceptions differed by socio-economic status or age, interpreting significance by setting a significance level of 0.05. These responses were then used to inform the interpretation of model results.

3. Results

3.1. Descriptive statistics: overview of sample population characteristics

Characteristics	All (n = 3213)	Group 1: Within 400m of a Silver Zone (n = 1276, 40%)	Group 2: Between 400 and 1 km of a Silver Zone (n = 1,956, 60%)	Significance tests comparing Group 1 vs Group 2
Gender	47% Men	47% Men	47% Men	Chisq (df = 1) 0.01, p = 0.91
	53% Women	53% Women	53% Women	
Ethnicity	84% Chinese	83% Chinese	84% Chinese	Chisq (df = 3) 3.50, p = 0.32
	8% Malay	9% Malay	8% Malay	
	6% Indian	6% Indian	6% Indian	
	2% others	1% others	2% others	
Marital Status	76% Married	75% Married	78% Married	Chisq (df = 3) 5.31, p = 0.15
	11% Single	12% Single	10% Single	
	6% Separated/ Divorced	6% Separated/Divorced	6% Separated/Divorced	
	7% Widowed	7% Widowed	6% Widowed	
Education Attainment	28% Primary or less	31% Primary or less	26% Primary or less	Chisq (df = 2) 20.4, p < 0.05
	42% Secondary	44% Secondary	41% Secondary	
	30% Post Secondary	26% Post Secondary	33% Post Secondary	
Income (SGD)	Mean = 3903	Mean = 3493	Mean = 4623	*t*-test (df = 3204) = −5.19, p < 0.05
	36% Low SES	37% Low SES	35% Low SES	Chisq (df = 2) 25.5, p < 0.05
	32% Mid SES	36% Mid SES	30% Mid SES	
	32% High SES	26% High SES	35% High SES	
Age at baseline	Mean = 59.0 years	Mean = 59.1 years	Mean = 59.0 years	*t*-test: (df = 2699) = 0.37, p = 0.72
	56% youngest age group	56% youngest age group	56% youngest age group	Chisq (df = 2) 0.67, p = 0.72
	23% middle age group	23% middle age group	23% middle age group	
	21% oldest age group	22% oldest age group	21% oldest age group	

Those living within 400m of a Silver Zone were largely similar to those living farther away in terms of gender, ethnicity, and age. However, the former were less likely have a post-secondary education and also significantly less monthly income at baseline, compared to those living further from a Silver Zone.

Additionally, older participants were more likely to be of lower SES than younger participants. For instance, about 63% of participants in the oldest age category were classified as having low SES, while 41% and 24% of those in the middle and youngest age category respectively were classified as low SES.

3.2. Model results

The base models suggest that on average, increases in Silver Zone access were not significantly related to changes in participant outcomes the year of Silver Zone opening, nor up to two years after opening. (See Appendix D).

For the oldest age group only, when their access to Silver Zones increased, their reported frequency of leaving home **reduced** one year after the opening of a new Silver Zone near their homes (see Table 1). The non-significant F-statistic for the model suggests that this perceived effect may in fact not be significant.

We also observe no significant relationship between Silver Zone access and outcomes of low SES individuals (Table 2). In contrast, for mid SES participants, we see a **lower frequency** of leaving the house one year after increased access to Silver Zones, compared to their low SES counterparts. Mid SES participants also reported having **lower social participation** the year of a new Silver Zone opening near their homes, compared to their low SES counterparts. In the models where the base reference SES category was set as mid SES (Table D.4, Appendix D), we found these inverse relationships between access to Silver Zones, frequency of leaving home and social participation were statistically significant for mid SES participants. Additionally, in the rebased models where the base reference SES was set as high SES, we also see a significant increase in the frequency of participants with High SES leaving home one year after increased access to Silver Zones (Table D.5 Appendix D).

Table 2 further shows that, one year after access to Silver Zones increased, social participation levels for high SES participants dropped more than their low SES counterparts. Additionally, two years after access to Silver Zones increased, self-reported general health of participants with high SES improved more than those with low SES (where we see no significant relationship between Silver Zone access and general health). However, the 'rebased' interaction models did not find the relationships between changes in Silver Zone access and the social participation or general health of high SES participants to be statistically significant (Appendix D).

Looking at the combination of age and SES, the oldest participants of low SES on average reported reduced frequency of leaving home the year after increasing access to Silver Zone (Table 3) However, for younger participants who were of low SES, we see a positive bump in their frequency of leaving home the year after increasing access to Silver Zone (see Appendix D, Table D.6). The non-significant F-statistic for this model however suggests that this observed effect may in fact not be significant. Along a similar vein, the oldest participants with low SES on average reported a significant drop in social satisfaction the year they experienced increased access to Silver Zone, whereas none of the other subgroups did (see Appendix D, Tables D.6 to D.8).

The Hausman tests confirm the appropriateness of utilizing individual fixed effects rather than random effects in our analysis. The low values of F-statistics and R-squared results however suggest that the contribution of the Silver Zone treatment to self-reported changes in individuals' outcomes may be small, if not non-significant**.** Robustness checks produced similar results as the main models presented here (Details can be made available from the corresponding author upon request).

3.3. Analyses of perceptions of Silver Zones

To aid the interpretation of the above model results, we analysed answers from 6462 SLP participants who responded to the survey questions on their perceptions of Silver Zones. 24.8% (n = 1606) indicated they were currently living near a Silver Zone. Of this group, 54% (n = 860) lived more than 400m, or approximately 5 min walk, away from a Silver Zone, while about 20% (n = 509) lived over 800m away, based on their reported addresses in 2021. For those who indicated they did not live near a Silver Zone, about 20% (n = 1016) had last recorded home addresses that actually were located within 400m of a Silver Zone. Fig. 2 below summarises the frequency distributions of respondents' distance to the nearest Silver Zone, differentiated by those who responded they had a Silver Zone nearby versus those who indicated they did not. This figure indicates substantial overlap between the two groups.

Of the respondents who indicated they lived near a Silver Zone, 49.1% (n = 788) said Silver Zones did not affect them at all, 45.4% (n = 729) indicated only positive effects from the scheme, 4.4% (n = 70) said they experienced both positive and negative effects; and

Table 1

Changes in distance to nearest Silver Zones and participant outcomes, with age interactions. Reference Age Group: Oldest.

	Leave Home	Avg Social Participation	Social Satisfaction	General Health
	(1)	(2)	(3)	(4)
Distance to nearest Silver Zone	−0.016 (0.079)	0.003 (0.033)	0.035 (0.025)	−0.015 (0.031)
Distance to nearest Silver Zone, One Year Lag	0.156* (0.066)	−0.079 (0.069)	0.007 (0.015)	−0.0003 (0.018)
Distance to nearest Silver Zone, Two Year Lag	0.037 (0.040)	−0.037 (0.023)	0.022 (0.015)	0.019 (0.015)
Distance to nearest Silver Zone:Age Youngest	0.027 (0.083)	0.018 (0.037)	−0.021 (0.027)	0.011 (0.033)
Distance to nearest Silver Zone:Age Middle	0.057 (0.093)	−0.017 (0.047)	−0.034 (0.031)	−0.016 (0.038)
Distance to nearest Silver Zone, One Year Lag:Age Youngest	−0.192** (0.073)	0.087 (0.074)	−0.007 (0.017)	−0.010 (0.020)
Distance to nearest Silver Zone, One Year Lag:Age Middle	−0.216* (0.108)	0.016 (0.078)	−0.007 (0.018)	−0.004 (0.023)
Distance to nearest Silver Zone, Two Year Lag:Age Youngest	−0.087~ (0.050)	0.030 (0.027)	−0.018 (0.018)	−0.018 (0.017)
Distance to nearest Silver Zone, Two Year Lag:Age Middle	−0.062 (0.061)	0.006 (0.032)	−0.031~ (0.019)	−0.018 (0.020)
Observations	7871	7862	11,076	11,076
Hausman Test Chi-square	57.07***	34.48***	15.37~	36.23***
F Statistic	1.328 (df = 9; 5041)	1.451 (df = 9; 5034)	1.202 (df = 9; 7998)	0.784 (df = 9; 7998)
R^2	0.002	0.003	0.001	0.001

Note: ~p < 0.1; *p < 0.05; **p < 0.01; ***p < 0.001, Standard Errors are in parenthesis.

Table 2
Changes in distance to nearest Silver Zones and participant outcomes, with SES Interactions. Reference SES group: Participants with low SES.

	Leave Home	Avg Social Participation	Social Satisfaction	General Health
	(1)	(2)	(3)	(4)
Distance to nearest Silver Zone	0.060 (0.039)	−0.030 (0.029)	0.026 (0.018)	−0.022 (0.021)
Distance to nearest Silver Zone, One Year Lag	−0.035 (0.046)	−0.060 (0.045)	0.003 (0.010)	−0.017 (0.014)
Distance to nearest Silver Zone, Two Year Lag	0.016 (0.034)	−0.036~ (0.019)	0.015 (0.011)	0.022~ (0.013)
Distance to nearest Silver Zone:Mid SES	−0.114~ (0.065)	0.105** (0.038)	−0.016 (0.025)	−0.008 (0.031)
Distance to nearest Silver Zone:High SES	−0.050 (0.053)	0.039 (0.035)	−0.014 (0.022)	0.031 (0.024)
Distance to nearest Silver Zone, One Year Lag:Mid SES	0.175* (0.071)	−0.006 (0.056)	0.005 (0.015)	0.026 (0.017)
Distance to nearest Silver Zone, One Year Lag:High SES	−0.054 (0.064)	0.111* (0.055)	−0.010 (0.014)	0.008 (0.017)
Distance to nearest Silver Zone, Two Year Lag:Mid SES	−0.110~ (0.056)	0.031 (0.026)	−0.019 (0.017)	−0.016 (0.018)
Distance to nearest Silver Zone, Two Year Lag:High SES	−0.005 (0.047)	0.022 (0.029)	−0.011 (0.015)	−0.036* (0.016)
Observations	7871	7862	11,076	11,076
Hausman Test Chisquare	45.24***	33.73***	17.97*	18.61*
F Statistic	2.149* (df = 9; 5041)	2.452** (df = 9; 5034)	0.828 (df = 9; 7998)	1.526 (df = 9; 7998)
R^2	0.004	0.004	0.001	0.002

Note: ~$p < 0.1$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$, Standard Errors are in parenthesis.

Table 3
Changes in distance to nearest Silver Zones and changes in participant outcomes, including one and two year lags, and SES Interactions. Reference SES group: Oldest Participants with Low SES.

	Leave Home	Avg Social Participation	Social Satisfaction	General Health
	(1)	(2)	(3)	(4)
Distance to nearest Silver Zone	0.061 (0.078)	−0.035 (0.042)	0.073* (0.036)	−0.058 (0.037)
Distance to nearest Silver Zone, One Year Lag	0.152* (0.076)	−0.094 (0.094)	0.013 (0.017)	−0.011 (0.023)
Distance to nearest Silver Zone, Two Year Lag	0.046 (0.044)	−0.035 (0.026)	0.006 (0.016)	0.0003 (0.017)
Distance to nearest Silver Zone:Higher SES, Younger	−0.058 (0.082)	0.063 (0.045)	−0.057 (0.037)	0.045 (0.039)
Distance to nearest Silver Zone:Higher SES, Oldest	−0.201 (0.174)	0.101 (0.068)	−0.103* (0.043)	0.109~ (0.059)
Distance to nearest Silver Zone:Low SES, Younger	−0.002 (0.088)	0.008 (0.056)	−0.071~ (0.041)	0.055 (0.044)
Distance to nearest Silver Zone, One Year Lag:Higher SES, Younger	−0.159~ (0.085)	0.101 (0.097)	−0.012 (0.018)	0.006 (0.024)
Distance to nearest Silver Zone, One Year Lag:Higher SES, Oldest	−0.009 (0.135)	0.058 (0.123)	−0.016 (0.034)	0.050 (0.034)
Distance to nearest Silver Zone, One Year Lag:Low SES, Younger	−0.284** (0.093)	0.051 (0.105)	−0.017 (0.020)	−0.010 (0.027)
Distance to nearest Silver Zone, Two Year Lag:Higher SES, Younger	−0.101~ (0.053)	0.030 (0.030)	−0.015 (0.017)	−0.013 (0.018)
Distance to nearest Silver Zone, Two Year Lag:Higher SES, Oldest	−0.032 (0.092)	−0.007 (0.051)	0.042 (0.034)	0.048 (0.032)
Distance to nearest Silver Zone, Two Year Lag:Low SES, Younger	−0.058 (0.063)	−0.002 (0.037)	0.015 (0.021)	0.038 (0.023)
Observations	7871	7862	11,076	11,076
Hausman Test Chisquare	63.99***	44.82***	20.17~	24.52*
F Statistic	1.542 (df = 12; 5038)	1.457 (df = 12; 5031)	2.051* (df = 12; 7995)	2.751*** (df = 12; 7995)
R^2	0.004	0.003	0.003	0.004

Note: ~$p < 0.1$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$, Standard Errors are in parenthesis.

only 1% (n = 16) reported negative effects only.

Participants reporting positive effects mostly pointed to improvements in travel safety as the main benefit (n = 718, or 89.9% of positive responses). Many also agreed that Silver Zones made travelling around their neighborhoods more pleasant (n = 394, 49.3%). In terms of behavior change, about one third of those reporting positive effects felt more inclined to walk around their neighborhoods (n = 257) whereas about one quarter (n = 205) indicated they were more likely to leave home because of the Silver Zone improvements. Of the relatively small numbers reporting negative effects, the main reasons offered were increased congestion (n = 30); a poorer experience of driving or being driven (n = 15) and a reduced ability to walk or cross roads (n = 15).

When looking at whether perceptions of Silver Zones differed by age, we observed that those who indicated 'no effect' from being near a Silver Zone were on average slightly younger at baseline (mean = 57.9) than those who indicated a positive effect only (mean = 59.3,t score = −5.06, df 1492.6, p value < 0.05). We found no other statistical differences in baseline age between those who found Silver Zones to have wholly positive effects and those indicating some negative effects from the Silver Zones, nor any differences between those who indicated no effect and those reporting negative effects.

Looking at the split of responses by baseline age category (Table 4), we see that while those in the oldest age category were most

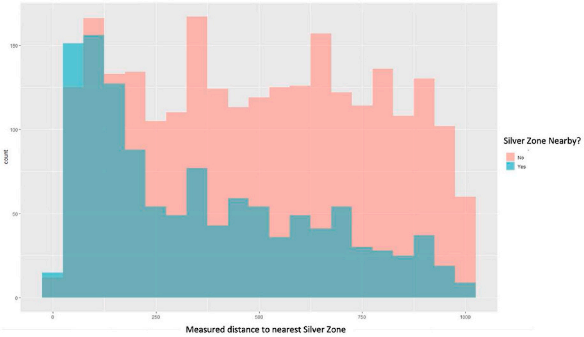

Fig. 2. Comparing frequency histograms of Participants' Distance to Nearest Silver Zone: those who indicated they lived near a Silver Zone versus those who indicated they did not.

likely to be positive, they were also more likely to indicate negative effects. In contrast, the youngest subgroup was most likely to perceive no impact.

Looking at the split of responses by baseline SES category (Table 5), we see that those classified as having low SES had the highest rates of positive responses and lowest rates of negative responses, while those with high SES had the most percentage of negative responses and lowest positive responses. Those who indicated only positive effects were significantly lower in baseline income (mean of 4.07 thousand SGD) compared to those who indicated some negative effects (mean = 6.12k, $t = -2.55$, $df = 97.838$, $p = 0.01$), as well as those indicating no effects (mean = 5.36k, $t = -3.429$, $df = 1439$, $p < 0.01$).

Finally, looking at the combination of age and SES categories (see Table 6), we see that respondents in the oldest age group and who were also of low SES were most likely to be positive about Silver Zones compared to other groups, whereas those who were also oldest but of either mid or high SES were more than twice as likely to be negative and half as less likely to be positive than their low SES counterparts.

4. Discussion

While there have been relatively few studies that empirically examine how pedestrian safety-oriented infrastructural programs affect residents' health and social outcomes, there is a widely-held belief that making neighborhoods more pedestrian-friendly encourages greater social participation and thus better health and social outcomes, particularly among older adults who face higher risks of social isolation. In testing out this hypothesis, we find little evidence of positive impacts of Silver Zone improvements on the self-reported social and health outcomes of older adults in Singapore, even though close to 50% of respondents who reported living near a Silver Zone had positive impressions of the scheme. While there are a relatively small number of available studies examining broader health impacts of traffic calming interventions beyond traffic-related collisions, crashes, deaths, and injuries (Cleland et al., 2020), our findings align with studies of seven sites in the UK where traffic calming improvements were implemented, between 2000 and 2004, which found little effect on actual levels of walking nor physical activity amongst adults, even though many participants reported that the changes made walking and cycling more pleasant (D. Webster et al., 2006). However, such 'null effects' may not be universal. Morrison (2004)'s study of a neighborhood in Glasgow, Scotland, six months before and after a traffic calming scheme, found substantial increases in observed pedestrian activity, except amongst pensioners aged over 60 years old. Similarly, a study based in Slovenia which surveyed 85 households' responses to traffic calming improvements in their neighborhood found that self-reported walking and cycling rates increased, but least so amongst those older than 65 (Balant and Lep, 2020).

One possible explanation, which is supported by our analyses of SLP participants' perceptions of Silver Zones, is that many of the older adults whose home addresses were close to a Silver Zone seemed unaware of this fact. This observation in turn suggests a lack of substantial interaction with the implemented changes despite relative proximity.

Another major gap in existing literature is how, despite intuitions that traffic calming schemes contribute to greater equity, there has been a lack of empirical studies documenting differentiated responses to traffic calming schemes by age or socioeconomic status. Our findings suggest the assumption that benefits from traffic calming interventions are equitably distributed may be too simplistic. Examining how associations between Silver Zone access and the various outcomes of interest might differ by age and socioeconomic class suggests that certain subgroups may be affected more than others. Worryingly, results from the models of the combination of SES

Table
4Cross tabulation of responses to Silver Zone by Age group.

	Youngest (n = 939)	Middle (n = 359)	Oldest (n = 308)
Negative	5.3%	4.2%	6.8%
No effect	54.3%	45.7%	37.7%
Positive	40.4%	50.1%	55.5%
	100%	**100%**	**100%**

Table
5Cross tabulation of responses to Silver Zone by SES group.

	Low SES (n = 490)	Mid SES (n = 553)	High SES (n = 505)
Negative	4.1%	4.7%	7.1%
No effect	44.1%	46.5%	58.0%
Positive	51.8%	48.8%	34.9%
	100%	**100%**	**100%**

Table
6Cross tabulation of responses to Silver Zone by SES & Age group.

	Oldest Age Group		Younger Age Group	
	Low SES (n = 169)	Higher SES (n = 91)	Low SES (n = 321)	Higher SES (n = 937)
Negative	4.7%	**13.2%**	3.7%	5.3%
No effect	34.3%	57.1%	49.2%	53.1%
Positive	**60.9%**	**29.7%**	47.0%	41.5%
	100%	**100%**	**100%**	**100%**

and age as a modifier suggest that oldest participants with low SES – the most vulnerable subgroup– were particularly likely to experience negative changes in social satisfaction after the opening of Silver Zones near them. One tentative reason for the negative relationship between Silver Zone access and participant outcomes is that the pedestrian safety-oriented improvements might be experienced as an impedance to walking. Silver Zones' efforts to 'channel' pedestrians away from typical and unsafe jaywalking behaviors towards safer 'formal' crossings (zebra crossings; signalized crossings) could be perceived by some as an inconvenience. In particular, older adults with walking difficulties may feel particularly inconvenienced by the extra steps needed to reach a formal crossing. This interpretation is inline with the responses to our survey questions, where a number of respondents (n = 15) reported a reduced ability to walk or cross roads due to the Silver Zones. As another reference point, a 2022 qualitative study of Silver Zones which interviewed 26 participants (ages 22 to 62), reported that some participants thought the traffic calming measures made traffic jams more common, and also made pedestrians more complacent and thus less vigilant when crossing the roads (Chng et al., 2022).

The reason we only see a significant relationship between Silver Zone access and reduced social satisfaction among the oldest participants with low SES might be because this group is most sensitive to changes in their neighborhood, given that they are likely to have more limited mobility and thus more confined to their particular neighborhoods. This vulnerable subgroup is likely to be less ambulant than their younger, richer counterparts and thus might require more than neighborhood infrastructural changes to improve social satisfaction, despite their positive attitudes towards Silver Zones. At the same time, the Silver Zone related changes that pose impedances to mobility discussed earlier might have been sufficient to affect their wellbeing.

Examining the modifying effect of SES produced somewhat unintuitive results. Our descriptive analyses of Silver Zone perceptions found lower SES participants to be more likely to perceive positive benefits than higher SES participants, which is a finding that aligns with expectations that higher SES individuals are more likely to travel by private motor vehicles and are thus more likely to experience inconveniences from slower car travel speeds from Silver Zones. Negative impressions that traffic calming schemes slowed vehicular traffic and thus inconvenienced those who drive are also inline with feedback gathered elsewhere in the world (Crouse, 2004). However, changes in Silver Zone access did not seem to have a significant impact on participants with low SES, despite this group being most likely to perceive Silver Zones positively. Modelling how the combination of SES and age might modify participants' responses to Silver Zones suggest a divergence between younger and older participants of low SES: younger low SES participants reported, on average, greater frequency of leaving home a year after Silver Zones were implemented near them while older participants reported the opposite. This age-specific divergence would explain why, on a whole, we initially observe no clear relationship between Silver Zone access and participant outcomes among those with low SES.

For participants of high SES, we see a significant increase in their frequency of leaving home one year after increased proximity to Silver Zones. Thus, despite their greater propensity to view Silver Zones negatively, those with high SES were the only ones who seemed to benefit from proximity to Silver Zones. It is challenging to speculate what might be driving this effect without more research, but other empirical studies on the link between SES and walking behaviors offer some tentative explanations to be further tested. Studies based in Hong Kong have found more highly educated adults engaged in more 'intra-neighborhood' walking for recreation than their less educated counterparts (Cerin et al., 2013) whereas less educated adults tended to walk more for transportation purposes than more educated adults (Cerin et al., 2012). Such findings are aligned to results from the U.S and the Netherlands (Kruger et al., 2008; Li et al., 2014; Kamphuis et al., 2009).

Studies also suggest that different types of walking might have different 'elasticities' of responses to neighborhood characteristics related to safety. For instance a study of pedestrians in Iran found 'hedonic' walking, which essentially is for enjoyment, to be substantially affected by safety from crime and traffic, whereas 'utilitarian' walking for a purpose (e.g. commuting, to carry out a task) was not (Mirzaei et al., 2018). A study of Beijing residents also found neighborhood characteristics associated with more exposure to traffic and therefore less safe pedestrian conditions, such as high population density and the greater density of road junctions, to be negatively associated with recreational walking and walking for daily affairs respectively, whereas conversely higher population density was associated with more 'commuting' related walking (Zhao and Wan, 2020).

Taken together, findings from these studies tentatively point to the possibility that neighborhood changes to improve pedestrian safety might have translated into more recreational walking, but only among higher SES adults, whereas lower SES adults might not be positively affected by safety improvements as walking for them tends to be more functional, and thus less responsive to safety changes.

Unexpectedly, participants classified as mid SES seemed to experience shorter term negative changes after increased access to Silver Zones, such as reduced frequency of leaving their homes one year after the opening of a new Silver Zone, as well as a decrease in social participation the year of. It is immediately not intuitive why this subpopulation may be more sensitive to any inconveniences posed by Silver Zones, compared to those with high or low SES.

Our study also found a disjoint between perceptions of Silver Zones and participant outcomes—specifically in terms of a significant drop in social satisfaction amongst oldest adults of low SES when a new Silver Zone was implemented near their homes, despite their perceptions of Silver Zones being more likely to be positive than the rest of their peers. Similarly, there is a disjoint between positive participant outcomes among high SES participants despite a relatively higher rate of negative perceptions than their lower SES peers. These discrepancies could be due to a lack of accurate awareness of nearby Silver Zones. Respondents living near Silver Zones might very well be unaware of their existence, and thus not report having any particular impression of Silver Zones, but yet still experience changes in their lives due to the scheme. While Silver Zones are marked by signages, Chng et al. (2022) reported that some residents called for more publicity beyond existing physical signages because these did not explain what a Silver Zone was, nor the scheme's intent. The lack of clear awareness of Silver Zones we find in our study suggests a need for more promotion and engagement with residents by local authorities. Available studies of public engagement around traffic calming efforts—albeit rather dated ones—have similarly recommended that, to build support and achieve greater success, authorities should open up their consultation process, including at the detailed design stage and particularly among older, long-established residents who may resist changes to their environments (Evans, 1994; Rahman et al., 2007; Taylor and Tight, 1997).

Another potential explanation is that there is a large variation in what older adults define as 'nearby' to them. Some may perceive a Silver Zone located 200m away as still too far to be considered nearby, whereas others might perceive a Silver Zone located twice as far away as still within the ambit of their neighbourhoods. This explanation is well-supported by studies showing wide variations in self-defined neighborhood boundaries among older adults (Finlay et al., 2023) and others (Charreire et al., 2016).

Either explanation would fit what was observed in the descriptive analyses of Silver Zone perceptions: which is that there was substantial variation in self-assessment of whether one lived near a Silver Zone or not, regardless of actual estimated distance to Silver Zones based on residential address.

Our findings here suggest that the reported perceptions of Silver Zones do not offer an accurate assessment of actual experiences of Silver Zones of all who may be affected, consciously or otherwise. Other studies elsewhere comparing objective measures of the impact of traffic calming interventions on vehicle speeds, traffic volume, injuries, noise, vibration and air pollution against public perceptions similarly found substantial discrepancies (D. C. Webster, 1998).

The practical implication of this finding is that researchers and policy-makers should thus be cautious when relying solely on self-reported perceptions of pedestrian safety schemes like the Silver Zones to assess their impact. Instead, assessments should also ideally be tied to more 'objective' measures, such as measurements of walking behaviours (e.g. collected through mobility apps or activity trackers). Panel studies like the SLP that collect health and social wellbeing measures also provide valuable avenues for assessment.

Another implication of our findings is that more research is needed to unpack the seemingly unintuitive relationships between participant SES and age, and their responses to Silver Zones that we found. In particular, findings that run counter to the commonly held hypothesis that traffic calming schemes are socially equitable by benefiting the less advantaged groups more than their more advantaged counterparts (Litman 1999) are concerning and should be further interrogated. In order to ensure that Silver Zones, and other similar pedestrian-oriented infrastructural changes, actually benefit older adults equally, and not just those with higher SES, policy-makers need to understand how awareness, perceptions and actual interactions with traffic safety related infrastructural changes, might differ by SES and age. Repeated qualitative interviews or focus groups with affected residents before and after the implementation of pedestrian-friendly infrastructural changes, coupled with more 'objective' measures of behaviors and individual outcomes, would be invaluable towards achieving this goal. As Singapore plans to implement more Silver Zones and pedestrian-friendly streets over the next few years, there are invaluable opportunities for more 'quasi-experimental' studies to help verify the actual causal links between pedestrian environment, perceptions, and behavior change.

Finally, our model fit statistics suggest that the contribution of Silver Zone treatment to self-reported change in participant outcomes were relatively small. Policy-makers might thus also wish to test whether a targeted outreach and publicity campaign would change older residents' awareness and perceptions of existing Silver Zones, improve their likelihood of leaving their homes to participate socially, and thus have a bigger impact on improving outcomes. If effective, future rollouts of pedestrian safety infrastructural upgrades could be coupled with more intensive and targeted engagement and outreach efforts than might be provided currently.

4.1. Limitations

While one of the key strengths of this study is its use of longitudinal data to examine the possible effects of pedestrian safety improvements, it is nevertheless also subject to several important methodological and data-related limitations. First, our analysis relies on self-reported outcomes which might be subject to self-reporting biases. Another limitation is that, while utilising longitudinal data to conduct a 'before' and 'after' intervention comparison might minimise confounding from time-invariant factors, there is still a potential for confounding from unobservable time-variant factors (Sun et al., 2023), like changes in individuals' preferences or values over time. A third limitation is that, while we tested the possibility that Silver Zone changes might coincide with other built environmental changes such as changes in public transport infrastructure, food retail outlets and so on, which could confound our findings, and found this to be unlikely, there is nevertheless a possibility that other unmeasured or unmeasurable changes might be in play (e.g. changes in neighborhood composition pre and post that we cannot test for due to lack of sufficiently fine-grained spatio--temporal population data).

Furthermore, as the SLP survey did not survey participants on their perceptions of neighborhood walkability or pedestrian safety between 2015 and 2020, our regression models could not formally test for the 'causal pathway' of Silver Zone implementation affecting social participation through changing perceptions of walkability and thus walking behavior. Instead, our best efforts to test this hypothesized causal pathway was to survey SLP participants in 2023, on their perceptions of whether Silver Zones improved neighborhood walkability and pedestrian safety. While these responses were not included in the regression models (because of time period mismatch), we integrated the descriptive analyses of these as best we could into the interpretation of our regression model findings.

Given data limitations, we were thus unable to pinpoint the precise causal mechanisms undergirding the observed relationships, and thus were only able to propose tentative hypotheses. In order to verify these tentative hypotheses and to convincingly explain the seemingly counter-intuitive relationships we observed, more in-depth research will be needed. These would ideally include an examination of changes in travel behaviors such as amount of walking versus driving/being driven over the short, medium and longer-term, as well as more in-depth interviews to understand how older adults of different socioeconomic status and/or age bands might perceive and interact with the Silver Zone-related infrastructural changes differently.

5. Conclusion

By utilizing a 'quasi-experiment' approach to estimate the impact of pedestrian safety focused infrastructural improvements on the social and health outcomes of older adults in Singapore, this study offers insights about the links between walkability, social participation and health in a hitherto understudied geographical context. We find evidence that, unlike what conventional wisdom suggests, the positive benefits of these infrastructural changes do not necessarily favor those of lower socioeconomic class. Our findings suggest that the oldest participants with low SES – a particularly vulnerable subgroup – experienced negative changes after the opening of Silver Zones near them, as did those classified as mid SES. In contrast, our findings suggest that new Silver Zones might have a positive effect on older adults of high SES. We also observed a mismatch between perceptions of Silver Zones, actual exposure, and participant outcomes, which might explain why we found increased Silver Zone exposure to have only small contributions to self-reported change in participant outcomes. Our findings point to the need for more targeted outreach and publicity campaigns to increase accurate awareness of Silver Zone initiatives, as well as the importance of going beyond self-reported perceptions when assessing the success of pedestrian safety schemes like the Silver Zones. Our findings provide an exploratory first step in drawing links between pedestrian safety improvements and older adults' social and health outcomes—links which should in turn be further investigated with additional sources of data and methods, both qualitative and quantitative.

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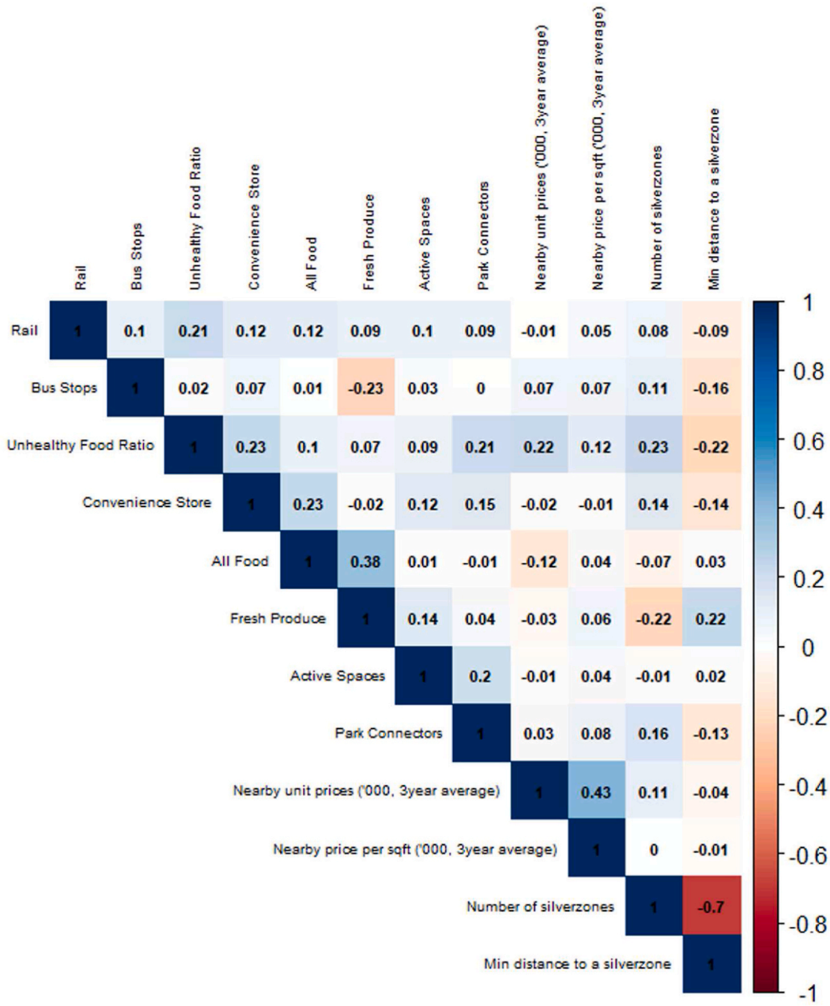
CRediT authorship contribution statement

Shin Bin Tan: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **William Tov:** Writing – review & editing, Methodology, Conceptualization. **Paulin Straughan:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A



Appendix B

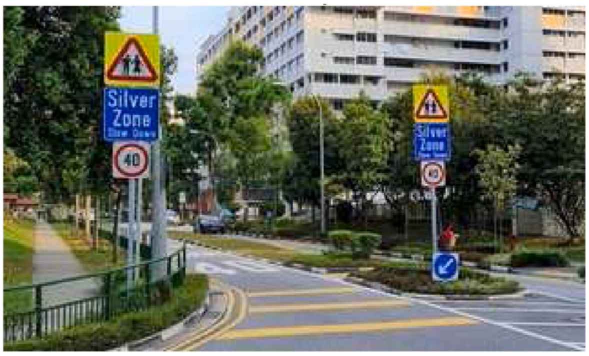
Mean distance weighted density scores (as of 2021) of neighborhood characteristics around residential buildings located within 3 distance bands (<400m, 400m-1km, >1 km)

Neighborhood characteristics	Within 400m (n = 6357)	400—1 km (n = 19,405)	Beyond 1 km (n = 77,530)
Rail	0.45	0.31	0.41
Bus Stops	104.54	90.13	67.41
Convenience stores	1.48	0.85	0.72
Prepared Food outlets	63.18	51.87	42.16
Markets/Supermarkets	1.98	1.25	0.84
Parks, Open Spaces, Recreational Spaces	163.53	203.43	497.60
Park Connectors	8.14	6.46	5.84
Nearby unit prices ('000, 3 year average)	972.68	1630.04	2209.39

Appendix C

Introduction to questions:

Since 2014, the Land Transport Authority has implemented 'Silver Zones' in residential neighborhoods to improve road safety. Improvements under the 'Silver Zones' programme include road redesigns to slow traffic and additional signage indicating speed limits. Here is a picture of what a typical Silver Zone looks like.



Q1: To the best of your knowledge, is there **a Silver Zone near your home?** Yes/No

Source: LTA.gov.sg
If answer is 'Yes', to proceed with Q2.

Q2: Of the following statements, please pick the one you agree with most:

a. The Silver Zone near my home has benefited me
b. The Silver Zone near my home has negatively affected me
c. The Silver Zone near my home has both benefited and negatively affected me
d. I have not been affected by the Silver Zone at all

If option a or c was chosen for Q2, to proceed with Q3.

Q3: What are the benefits you experienced from the Silver Zone? Please pick all options that you agree with:

a. The Silver Zone has made it safer for me to travel around my neighborhood
b. The Silver Zone has made it more pleasant to travel around my neighborhood
c. I am now more likely to leave my home for activities because of the Silver Zone
d. I am now more likely to walk around my neighborhood
e. Other positive changes include: _________ (open ended question)

If option b or c was chosen for Q2, to proceed with Q4.

Q4. How has the Silver Zone affected you negatively?:_____________*(open ended question)*

Appendix D. Base Models and 'Rebased' Models where Reference Groups for Interaction Analyses were changed

Table D.1
Longitudinal two-way fixed effects model of changes in distance to nearest Silver Zones and in participant outcomes

	Leave Home	Avg Social Participation	Social Satisfaction	General Health
	(1)	(2)	(3)	(4)
Distance to nearest Silver Zone	0.012 (0.026)	0.011 (0.015)	0.016 (0.010)	−0.011 (0.011)
Distance to nearest Silver Zone, One Year Lag	−0.006 (0.030)	−0.021 (0.023)	0.002 (0.007)	−0.006 (0.008)
Distance to nearest Silver Zone, Two Year Lag	−0.020 (0.025)	−0.021 (0.013)	0.006 (0.007)	0.006 (0.008)
Observations	7871	7862	11,076	11,076
Hausman Test Chisquare	37.88***	22.5***	7.7*	19.27***
F Statistic	0.403 (df = 3; 5047)	1.262 (df = 3; 5040)	1.222 (df = 3; 8004)	1.074 (df = 3; 8004)
R^2	0.0002	0.001	0.0005	0.0004

Note: ~p < 0.1; *p < 0.05; **p < 0.01; ***p < 0.001, Standard Errors are in parenthesis.

Table D.2
Youngest age group as reference group

	Leave Home	Avg Social Participation	Social Satisfaction	General Health
	(1)	(2)	(3)	(4)
Distance to nearest Silver Zone	0.011 (0.028)	0.021 (0.018)	0.015 (0.012)	−0.004 (0.013)
Distance to nearest Silver Zone, One Year Lag	−0.036 (0.033)	0.008 (0.028)	−0.0004 (0.009)	−0.010 (0.009)
Distance to nearest Silver Zone, Two Year Lag	−0.050 (0.034)	−0.007 (0.017)	0.004 (0.010)	0.001 (0.010)
Distance to nearest Silver Zone:Age Middle	0.030 (0.056)	−0.035 (0.038)	−0.014 (0.022)	−0.028 (0.026)
Distance to nearest Silver Zone:Age Oldest	−0.027 (0.083)	−0.018 (0.037)	0.021 (0.027)	−0.011 (0.033)
Distance to nearest Silver Zone, One Year Lag:Age Middle	−0.023 (0.092)	−0.071 (0.045)	0.0004 (0.013)	0.006 (0.018)
Distance to nearest Silver Zone, One Year Lag:Age Oldest	0.192** (0.073)	−0.087 (0.074)	0.007 (0.017)	0.010 (0.020)
Distance to nearest Silver Zone, Two Year Lag:Age Middle	0.024 (0.057)	−0.025 (0.028)	−0.013 (0.015)	−0.00005 (0.016)
Distance to nearest Silver Zone, Two Year Lag:Age Oldest	0.087~ (0.050)	−0.030 (0.027)	0.018 (0.018)	0.018 (0.017)
Observations	7871	7862	11,076	11,076
Hausman Test Chi-square	57.07***	34.48***	15.37~	36.23***
F Statistic	1.328 (df = 9; 5041)	1.451 (df = 9; 5034)	1.202 (df = 9; 7998)	0.784 (df = 9; 7998)
R^2	0.002	0.003	0.001	0.001

Note: ~p < 0.1; *p < 0.05; **p < 0.01; ***p < 0.001, Standard Errors are in parenthesis.

Table D.3
'Middle' age group as reference group

	Leave Home	Avg Social Participation	Social Satisfaction	General Health
	(1)	(2)	(3)	(4)
Distance to nearest Silver Zone	0.041 (0.051)	−0.014 (0.034)	0.001 (0.019)	−0.031 (0.023)
Distance to nearest Silver Zone, One Year Lag	−0.059 (0.087)	−0.063~ (0.037)	−0.00002 (0.011)	−0.005 (0.016)
Distance to nearest Silver Zone, Two Year Lag	−0.025 (0.049)	−0.031 (0.023)	−0.009 (0.012)	0.001 (0.013)
Distance to nearest Silver Zone:Age Youngest	−0.030 (0.056)	0.035 (0.038)	0.014 (0.022)	0.028 (0.026)
Distance to nearest Silver Zone:Age Oldest	−0.057 (0.093)	0.017 (0.047)	0.034 (0.031)	0.016 (0.038)
Distance to nearest Silver Zone, One Year Lag:Age Youngest	0.023 (0.092)	0.071 (0.045)	−0.0004 (0.013)	−0.006 (0.018)
Distance to nearest Silver Zone, One Year Lag:Age Oldest	0.216* (0.108)	−0.016 (0.078)	0.007 (0.018)	0.004 (0.023)
Distance to nearest Silver Zone, Two Year Lag:Age Youngest	−0.024 (0.057)	0.025 (0.028)	0.013 (0.015)	0.00005 (0.016)
Distance to nearest Silver Zone, Two Year Lag:Age Oldest	0.062 (0.061)	−0.006 (0.032)	0.031~ (0.019)	0.018 (0.020)
Observations	7871	7862	11,076	11,076
Hausman Test Chi-square	57.07***	34.48***	15.37~	36.23***
F Statistic	1.328 (df = 9; 5041)	1.451 (df = 9; 5034)	1.202 (df = 9; 7998)	0.784 (df = 9; 7998)
R^2	0.002	0.003	0.001	0.001

Note: ~p < 0.1; *p < 0.05; **p < 0.01; ***p < 0.001, Standard Errors are in parenthesis.

Table D.4
'Middle' SES group as reference group

	Leave Home	Avg Social Participation	Social Satisfaction	General Health
	(1)	(2)	(3)	(4)
Distance to nearest Silver Zone	−0.054 (0.053)	0.075** (0.026)	0.010 (0.018)	−0.030 (0.023)
Distance to nearest Silver Zone, One Year Lag	0.140* (0.055)	−0.066~ (0.034)	0.008 (0.012)	0.009 (0.012)
Distance to nearest Silver Zone, Two Year Lag	−0.094~ (0.048)	−0.005 (0.019)	−0.004 (0.013)	0.006 (0.014)
Distance to nearest Silver Zone:Low SES	0.114~ (0.065)	−0.105** (0.038)	0.016 (0.025)	0.008 (0.031)
Distance to nearest Silver Zone:High SES	0.063 (0.064)	−0.065* (0.032)	0.002 (0.021)	0.039 (0.026)
Distance to nearest Silver Zone, One Year Lag:Low SES	−0.175* (0.071)	0.006 (0.056)	−0.005 (0.015)	−0.026 (0.017)
Distance to nearest Silver Zone, One Year Lag:High SES	−0.229** (0.070)	0.117* (0.047)	−0.016 (0.016)	−0.018 (0.016)
Distance to nearest Silver Zone, Two Year Lag:Low SES	0.110~ (0.056)	−0.031 (0.026)	0.019 (0.017)	0.016 (0.018)
Distance to nearest Silver Zone, Two Year Lag:High SES	0.104~ (0.058)	−0.009 (0.029)	0.008 (0.017)	−0.020 (0.016)
Observations	7871	7862	11,076	11,076
Hausman Test Chisquare	45.24***	33.73***	17.97*	18.61*
F Statistic	2.149* (df = 9; 5041)	2.452** (df = 9; 5034)	0.828 (df = 9; 7998)	1.526 (df = 9; 7998)
R^2	0.004	0.004	0.001	0.002

Note: ~p < 0.1; *p < 0.05; **p < 0.01; ***p < 0.001, Standard Errors are in parenthesis.

Table D.5
High SES group as reference group

	Leave Home	Avg Social Participation	Social Satisfaction	General Health
	(1)	(2)	(3)	(4)
Distance to nearest Silver Zone	0.010 (0.038)	0.009 (0.020)	0.012 (0.013)	0.009 (0.013)
Distance to nearest Silver Zone, One Year Lag	−0.089* (0.045)	0.051 (0.033)	−0.008 (0.011)	−0.009 (0.012)

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Table D.5 (*continued*)

	Leave Home (1)	Avg Social Participation (2)	Social Satisfaction (3)	General Health (4)
Distance to nearest Silver Zone, Two Year Lag	0.010 (0.036)	−0.014 (0.024)	0.004 (0.011)	−0.014 (0.011)
Distance to nearest Silver Zone:Low SES	0.050 (0.053)	−0.039 (0.035)	0.014 (0.022)	−0.031 (0.024)
Distance to nearest Silver Zone:Mid SES	−0.063 (0.064)	0.065* (0.032)	−0.002 (0.021)	−0.039 (0.026)
Distance to nearest Silver Zone, One Year Lag:Low SES	0.054 (0.064)	−0.111* (0.055)	0.010 (0.014)	−0.008 (0.017)
Distance to nearest Silver Zone, One Year Lag:Mid SES	0.229** (0.070)	−0.117* (0.047)	0.016 (0.016)	0.018 (0.016)
Distance to nearest Silver Zone, Two Year Lag:Low SES	0.005 (0.047)	−0.022 (0.029)	0.011 (0.015)	0.036* (0.016)
Distance to nearest Silver Zone, Two Year Lag:Mid SES	−0.104~ (0.058)	0.009 (0.029)	−0.008 (0.017)	0.020 (0.016)
Observations	7871	7862	11,076	11,076
Hausman Test Chisquare	45.24***	33.73***	17.97*	18.61*
F Statistic	2.149* (df = 9; 5041)	2.452** (df = 9; 5034)	0.828 (df = 9; 7998)	1.526 (df = 9; 7998)
R^2	0.004	0.004	0.001	0.002

Note: ~$p < 0.1$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$, Standard Errors are in parenthesis.

Table D.6
Low SES, Younger age group as reference group

	Leave Home (1)	Avg Social Participation (2)	Social Satisfaction (3)	General Health (4)
Distance to nearest Silver Zone	0.059 (0.042)	−0.027 (0.038)	0.001 (0.020)	−0.002 (0.025)
Distance to nearest Silver Zone, One Year Lag	−0.132* (0.055)	−0.043 (0.047)	−0.004 (0.012)	−0.020 (0.016)
Distance to nearest Silver Zone, Two Year Lag	−0.012 (0.048)	−0.037 (0.027)	0.021 (0.015)	0.038* (0.017)
Distance to nearest Silver Zone:Higher SES, Younger	−0.056 (0.049)	0.054 (0.041)	0.014 (0.022)	−0.010 (0.027)
Distance to nearest Silver Zone:Higher SES, Oldest	−0.199 (0.161)	0.093 (0.066)	−0.032 (0.031)	0.054 (0.052)
Distance to nearest Silver Zone:Low SES, Oldest	0.002 (0.088)	−0.008 (0.056)	0.071~ (0.041)	−0.055 (0.044)
Distance to nearest Silver Zone, One Year Lag:Higher SES, Younger	0.125~ (0.066)	0.050 (0.053)	0.005 (0.014)	0.016 (0.018)
Distance to nearest Silver Zone, One Year Lag: Higher SES, Oldest	0.275* (0.123)	0.007 (0.092)	0.001 (0.032)	0.060* (0.030)
Distance to nearest Silver Zone, One Year Lag:Low SES, Oldest	0.284** (0.093)	−0.051 (0.105)	0.017 (0.020)	0.010 (0.027)
Distance to nearest Silver Zone, Two Year Lag: Higher SES, Younger	−0.043 (0.057)	0.033 (0.030)	−0.030~ (0.017)	−0.051** (0.019)
Distance to nearest Silver Zone, Two Year Lag: Higher SES, Oldest	0.026 (0.094)	−0.005 (0.052)	0.027 (0.033)	0.010 (0.032)
Distance to nearest Silver Zone, Two Year Lag:Low SES, Oldest	0.058 (0.063)	0.002 (0.037)	−0.015 (0.021)	−0.038 (0.023)
Observations	7871	7862	11,076	11,076
Hausman Test Chisquare	63.99***	44.82***	20.17~	24.52*
F Statistic	1.542 (df = 12; 5038)	1.457 (df = 12; 5031)	2.051* (df = 12; 7995)	2.751 (df = 12; 7995)
R^2	0.004	0.003	0.003	0.004

Note: ~$p < 0.1$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$, Standard Errors are in parenthesis.

Table D.7
Higher SES, Younger age group as reference group

	Leave Home (1)	Avg Social Participation (2)	Social Satisfaction (3)	General Health (4)
Distance to nearest Silver Zone	0.003 (0.029)	0.027 (0.017)	0.015 (0.011)	−0.013 (0.012)
Distance to nearest Silver Zone, One Year Lag	−0.007 (0.039)	0.007 (0.026)	0.001 (0.008)	−0.004 (0.009)
Distance to nearest Silver Zone, Two Year Lag	−0.055 (0.035)	−0.005 (0.016)	−0.008 (0.009)	−0.013 (0.009)
Distance to nearest Silver Zone:Higher SES, Oldest	−0.144 (0.159)	0.038 (0.056)	−0.046~ (0.027)	0.064 (0.047)
Distance to nearest Silver Zone:Low SES, Younger	0.056 (0.049)	−0.054 (0.041)	−0.014 (0.022)	0.010 (0.027)
Distance to nearest Silver Zone:Low SES, Oldest	0.058 (0.082)	−0.063 (0.045)	0.057 (0.037)	−0.045 (0.039)
Distance to nearest Silver Zone, One Year Lag:Higher SES, Oldest	0.150 (0.117)	−0.043 (0.083)	−0.005 (0.031)	0.044 (0.027)
Distance to nearest Silver Zone, One Year Lag:Low SES, Younger	−0.125~ (0.066)	−0.050 (0.053)	−0.005 (0.014)	−0.016 (0.018)
Distance to nearest Silver Zone, One Year Lag:Low SES, Oldest	0.159~ (0.085)	−0.101 (0.097)	0.012 (0.018)	−0.006 (0.024)
Distance to nearest Silver Zone, Two Year Lag:Higher SES, Oldest	0.069 (0.087)	−0.037 (0.047)	0.057~ (0.031)	0.061* (0.028)

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Table D.7 (*continued*)

	Leave Home	Avg Social Participation	Social Satisfaction	General Health
	(1)	(2)	(3)	(4)
Distance to nearest Silver Zone, Two Year Lag:Low SES, Younger	0.043 (0.057)	−0.033 (0.030)	0.030~ (0.017)	0.051** (0.019)
Distance to nearest Silver Zone, Two Year Lag:Low SES, Oldest	0.101~ (0.053)	−0.030 (0.030)	0.015 (0.017)	0.013 (0.018)
Observations	7871	7862	11,076	11,076
Hausman Test Chisquare	63.99***	44.82***	20.17~	24.52*
F Statistic	1.542 (df = 12; 5038)	1.457 (df = 12; 5031)	2.051* (df = 12; 7995)	2.751 (df = 12; 7995)
R^2	0.004	0.003	0.003	0.004

Note: ~p < 0.1; *p < 0.05; **p < 0.01; ***p < 0.001, Standard Errors are in parenthesis.

Table D.8
Higher SES, Oldest age group as reference group

	Leave Home	Avg Social Participation	Social Satisfaction	General Health
	(1)	(2)	(3)	(4)
Distance to nearest Silver Zone	−0.140 (0.157)	0.066 (0.054)	−0.031 (0.025)	0.051 (0.046)
Distance to nearest Silver Zone, One Year Lag	0.143 (0.112)	−0.036 (0.079)	−0.003 (0.031)	0.040 (0.026)
Distance to nearest Silver Zone, Two Year Lag	0.014 (0.082)	−0.042 (0.045)	0.049 (0.030)	0.048~ (0.027)
Distance to nearest Silver Zone:Higher SES, Younger	0.144 (0.159)	−0.038 (0.056)	0.046~ (0.027)	−0.064 (0.047)
Distance to nearest Silver Zone:Low SES, Younger	0.199 (0.161)	−0.093 (0.066)	0.032 (0.031)	−0.054 (0.052)
Distance to nearest Silver Zone:Low SES, Oldest	0.201 (0.174)	−0.101 (0.068)	0.103* (0.043)	−0.109~ (0.059)
Distance to nearest Silver Zone, One Year Lag:Higher SES, Younger	−0.150 (0.117)	0.043 (0.083)	0.005 (0.031)	−0.044 (0.027)
Distance to nearest Silver Zone, One Year Lag:Low SES, Younger	−0.275* (0.123)	−0.007 (0.092)	−0.001 (0.032)	−0.060* (0.030)
Distance to nearest Silver Zone, One Year Lag:Low SES, Oldest	0.009 (0.135)	−0.058 (0.123)	0.016 (0.034)	−0.050 (0.034)
Distance to nearest Silver Zone, Two Year Lag:Higher SES, Younger	−0.069 (0.087)	0.037 (0.047)	−0.057~ (0.031)	−0.061* (0.028)
Distance to nearest Silver Zone, Two Year Lag:Low SES, Younger	−0.026 (0.094)	0.005 (0.052)	−0.027 (0.033)	−0.010 (0.032)
Distance to nearest Silver Zone, Two Year Lag:Low SES, Oldest	0.032 (0.092)	0.007 (0.051)	−0.042 (0.034)	−0.048 (0.032)
Observations	7871	7862	11,076	11,076
Hausman Test Chisquare	63.99***	44.82***	20.17~	24.52*
F Statistic	1.542 (df = 12; 5038)	1.457 (df = 12; 5031)	2.051* (df = 12; 7995)	2.751 (df = 12; 7995)
R^2	0.004	0.003	0.003	0.004

Note: ~p < 0.1; *p < 0.05; **p < 0.01; ***p < 0.001, Standard Errors are in parenthesis.

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