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Research Paper

Exploring how socioeconomic status affects neighbourhood environments' effects on obesity risks: A longitudinal study in Singapore

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HIGHLIGHTS

- Study of how socioeconomic status (SES) modifies neighbourhoods' effect on BMI.
- Based in Singapore, which has less structural confounding from spatial segregation.
- More park connectors associated with BMI decrease for higher SES moms; inverse for lower SES.
- Increased access to bus stops associated with BMIz increase of lower SES children; inverse for higher SES.
- Effect of urban interventions might be modified by socioeconomic status.

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ABSTRACT

Research on how socioeconomic status interacts with neighbourhood characteristics to influence disparities in obesity outcomes is currently limited by residential segregation-induced structural confounding, a lack of empirical studies outside the U.S. and other 'Western' contexts, and an over-reliance on cross-sectional analyses. This study addresses these challenges by examining how socioeconomic status modifies the effect of accumulated exposures to obesogenic neighbourhood environments on children and mothers' BMI, drawing from a longitudinal mother-child birth cohort study in Singapore, an Asian city-state with relatively little residential segregation. We find that increased access to park connectors was associated with a decrease in BMI outcomes for mothers with higher socioeconomic status, but an increase for those with lower socioeconomic status. We also find that increased access to bus stops was associated with an increase in BMIz of children with lower socioeconomic status, but with a decrease in BMIz of children with higher socioeconomic status, while increased access to rail stations was associated with a decrease in BMIz of children with lower socioeconomic status only. Our results suggest that urban interventions might have heterogeneous effects by socioeconomic status.

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1. Introduction

Obesity has been observed to follow a socioeconomic gradient, particularly in high and middle income countries, where less well-off adults and children typically have higher rates of obesity (Katzmarzyk et al., 2019; Vazquez & Cubbin, 2020). Explanations for these disparities offered in previous literature include the idea that income and time scarcity impede one's ability to eat healthier foods, which tend to be more expensive and time-consuming to prepare than less nutritious items (Rao et al., 2013; Venn & Strazdins, 2017); the high cost of taste formation for healthy foods amongst children (Daniels et al., 2012); time scarcity as a barrier to leisure time exercise (Venn & Strazdins, 2017); relations between low socioeconomic status and stress, which itself is a barrier to 'healthy' behaviours (Bickel et al., 2014; Hemmingsson, 2018); among other individual and household-level factors.

Another frequently cited explanation for these disparities is that poor households tend to reside in obesogenic environments that promote weight gain (Rossen, 2014; Vargas et al., 2017). Dimensions of the built environment commonly theorised to affect obesity risks include the food environment, which refers to the types of food available for purchase within the neighbourhood. Neighbourhood food environments that lack fresh produce or are overabundant in processed and fast foods are considered obesogenic (Gamba et al., 2015). Greater access to establishments selling prepared food has also been associated with eating out more (An et al., 2020; Penney et al., 2017)— a risk factor for higher energy, fat intake and higher body weight (Bezerra et al., 2012; Penney et al., 2017; Zang et al., 2018; Zeng & Zeng, 2018). Second, obesity risks have also been linked to the extent to which neighbourhoods support active mobility. Scholars have linked use of public transport to more physical activity due to walking required to reach public transit stations, compared to driving (Koohsari et al., 2015; Sahlqvist et al., 2012). Third, the availability of recreational spaces, such as parks and playgrounds, could provide residents with more opportunities for physical activity and exercise (Ferdinand et al., 2012; Mackenbach et al., 2014).

More recently, researchers have also stressed the importance of examining how individual characteristics such as socioeconomic status (SES) might modify built environments' effects on obesity and obesity-related behaviours (Lovasi et al., 2009; Mackenbach et al., 2019). SES might affect the relationship between environment and obesity risks through food choices and physical activity. For instance, higher income individuals might be less bounded by their immediate residential surroundings as they typically have more resources to support travelling further than poorer individuals, such as access to a private car which can be expensive (Li & Kim, 2017; Mackenbach et al., 2019). Higher SES individuals may also be more responsive to changes in their neighbourhood because they have more flexibility and resources to adjust their consumption habits and lifestyle choices than economically-constrained individuals.

A clear understanding of whether and how SES might modify built environment effects on obesity is important in order to guide urban planning and public health interventions to reduce disparities in obesity and other related outcomes. So far, such studies remain relatively scarce (Jones-Smith et al., 2013; Smith et al., 2017), making it difficult to formulate appropriate policy interventions.

In addition to insufficient empirical research, the study of how socioeconomic status, built environment characteristics and health outcomes interact faces other challenges, such as structural confounding associated with social stratification or other selection processes. When poorer populations are systematically separated from richer populations through socio-spatial residential segregation, it becomes very difficult to estimate neighbourhood effects on a person's health separately from the effects of being poor (Messer et al., 2010; Oakes, 2004), or from the broader, macro-level processes that created a segregated landscape in the first place (Acevedo-Garcia & Osypuk, 2008). Furthermore, if social sorting results in an urban landscape where very few low-income individuals live in well-resourced, 'healthy', neighbourhoods, then any effort to extrapolate the impact of living in such neighbourhoods on these individuals' health would be 'off the support' of existing data (Messer et al., 2010; Oakes, 2004; Vafaei, Pickett, Zunzunegui, & Alvarado, 2016).

To date, studies on neighbourhood characteristics and obesity and related outcomes have primarily focused on so-called 'Western contexts': North America, Europe, Australia, New Zealand (Wilding et al., 2019; McGrath et al., 2015; Timperio et al., 2015). The over-representation of 'Western contexts', where patterns of racial/ethnic and socioeconomic segregation are striking, poses a challenge to the validity of existing findings (Lichter et al., 2016; Musterd et al., 2017) especially in non-Western contexts. Additionally, given the rapid increase in obesity prevalence in Asia (Ramachandran & Snehalatha, 2010), more research is needed to understand how built environments in Asian cities affect obesity risks, especially as there are significant differences between Western and Asian cities in terms of food environments (Caspi et al., 2017; Kim et al., 2016), built environment and residential segregation patterns (Cerin et al., 2011; Kim et al., 2016), food cultures, nutritional beliefs (Lim & van Dam, 2020; Rozin et al., 1999), and attitudes towards physical activity (Bauman et al., 2012; Haase et al., 2004).

Currently, empirical analyses around adiposity and environment factors largely consist of cross-sectional approaches (Drewnowski et al., 2020; Feng et al., 2010; Wilding et al., 2019), which have several disadvantages. First, cross-sectional analyses are often biased by confounding due to neighbourhood self-selection, which precludes the identification of causal mechanisms (Arcaya et al., 2016). Second, as neighbourhood effects on obesity are likely to accumulate over one's life course, static snapshots of neighbourhood environments fail to fully capture longer term exposure to neighbourhood conditions that change due to residential mobility and urban development (Letarte et al., 2020; Yang & South, 2018).

Furthermore, while associations between parental obesity and child obesity have been well-established (Wang et al., 2017), many studies focus on genetic and epigenetic inheritance (Wu & Suzuki, 2006); 'lifestyle' choices or parental modelling of obesogenic behaviours (Pinard et al., 2012; Wardle et al., 2001) as explanatory pathways. While scholars have acknowledged that shared environmental factors might also shape associations between parent and child obesity (Keane et al., 2012), there have been few studies empirically interrogating these broader environmental explanations, with a notable expectation being Saelens et al. (2012). More empirical research is needed to examine the differences in parents' and children's interactions with the same built environment characteristics vis-à-vis obesity risks.

The primary question for our study is: How does socioeconomic status affect the relationship between obesogenic neighbourhood characteristics—specifically food environments, active mobility infrastructure and recreational spaces—and obesity risks for mothers and their children in Singapore? We examine this question in ways that specifically address the above-mentioned challenges.

First, this study side-steps residential segregation as a structural confounder, by being situated in an urban context that is comparatively less spatially segregated. Singapore is a densely developed city-state in Southeast Asia, with a population of about 5.7 million, and a land area of approximately 728 square kilometres as of 2020. The largest ethnic group in Singapore is the Chinese, who make up 74.3% of the resident population, followed by Malays (13.5%) and Indians (9.0%) (Department of Statistics Singapore, 2020). Researchers have observed an inverse relationship between overweight and obesity risks with socioeconomic status among Singaporean women, though not consistently for men—findings that are in line with research from other developed countries. Scholars have sought to explain this difference by invoking the different social value thinness holds for men and women. Insofar as time and financial resources support the pursuit of a desired body form, higher SES individuals have more resources at their disposal to help them conform to socially valued body forms than lower SES individuals (Malhotra et al., 2013; Park et al., 2020; Sabanayagam et al., 2009, 2007; Wang et al., 2016). The 2013 National Health Surveillance Survey found that 20.7% of Malays, 14.0% of Indians and 5.9% of Chinese had obesity (Lee et al., 2016). These differences have been partially attributed to ethnic group differences in socioeconomic status, as the Malay population in Singapore is less socioeconomically well-off than the Chinese and Indian populations (Singstat, 2016). Nevertheless, even after accounting for socioeconomic differences, studies have found non-Chinese ethnic minorities to be at higher risks of having obesity (Ong et al., 2009; Park et al., 2020; Wang et al., 2016). While the precise mechanisms by which these racial/ ethnic health disparities occur in Singapore are understudied, scholars have suggested social and environmental reasons for why they might be so (Naidoo et al., 2017; Park et al., 2020).

In terms of built environment characteristics, Singapore has an extensive public transit network of buses and train lines, a substantial provision of parks and open spaces (Tan & Samsudin, 2017), as well as a vibrant food scene with ample, relatively low-cost options for eating out, such that an estimated 60% of people eat out at least four times a week (HPB, 2013). The residential integration of different socioeconomic and ethnic groups is another notable feature of Singapore's built environment. Since 1989, Singapore has enforced a policy that imposes quotas on ethnic composition of public housing estates, where over 80 percent of the country's population lives. This Ethnic Integration Policy (EIP) imposes constraints on housing allocations and unit re-sale transactions based on owners and buyers' ethnicity, to ensure that each housing block would broadly reflect national ethnic proportions. Apart from the EIP, policy-makers have also articulated their commitment to socioeconomic spatial integration, and in explicitly planning for a mix of different housing types to cater for different income groups within each neighbourhood (Ho, 2013; Shanmugaratnam 2015, 2014; Sim et al., 2003; Tan & Samsudin, 2017). Our estimation of Singapore's socioeconomic and ethnic segregation suggests that Singapore's levels of residential segregation are lower compared to cities in the U.S and Europe (See Appendix A). Furthermore, Singapore takes a top-down approach to urban planning and development that is ostensibly guided by 'objective' planning norms such as a provision of 0.8 ha of park space per thousand persons (Tan & Samsudin, 2017). Singapore's approach arguably provides a more egalitarian distribution of urban resources, compared to cities operating on relatively unfettered 'free market' models of urban development (Pulido, 2000).

By studying the Singapore context, this study also adds to the small pool of empirical evidence of how built environments in Asia might relate to obesity-related outcomes. To date, no study has examined the relationship between neighbourhood environmental characteristics and obesity risks in Singapore, with the exception of Park et al.'s (2020) paper, which analyses how neighbourhood SES, amongst other factors, contributes to obesity risks among adults. There are no recent studies based in Singapore that explicitly examine how child obesity outcomes differ by family socioeconomic status. Finally, unlike the bulk of existing, cross-sectional research on neighbourhood effects on health, this study explicitly examines the impact of accumulated neighbourhood exposures, by utilising a longitudinal dataset collected within a mother–child cohort study described in the next section. Besides the advantage of being able to examine accumulated exposures, using longitudinal approaches also enables the use of analytical techniques, such person-level fixed effects in regression analyses, which can better account for potential confounding from residential self-selection than cross-sectional approaches (Arcaya et al., 2016; Diez Roux, 2004).

2. Data and methods

2.1. Data source and key individual-level characteristics

We used data from a longitudinal cohort study, "Growing Up in Singapore Towards healthy Outcomes" (GUSTO). 1247 pregnant women (55.9% Chinese, 26.1% Malay and 18.0% Indian ethnicity) attending their first trimester antenatal dating ultrasound scan at two major public maternity units between June 2009 and September 2010 were recruited for the study. Detailed interviews were conducted at recruitment and at 26– 28 weeks gestation, to capture demographic, socioeconomic, lifestyle, and other data. Subsequent measurements of their infants were made at birth, with periodic follow-ups with both children and mothers at regular intervals throughout childhood to track a variety of outcomes, including height and weight. Specifically, anthropometric measurements were taken of the children at 3 weeks, 3, 9, 12, 15, 18, 24 and 36 months (Soh et al., 2014), and yearly henceforth. For mothers, height and weight measurements were taken at 18 months, Year 4 and Year 6 postpartum. Additionally, information on participants' addresses were collected and updated throughout the study, which allows for detailed mapping of participants' residential history.

For this study, the outcome variables of interest are BMI age and sex-adjusted Z-scores (BMIz) for the children, calculated according to WHO guidelines (de Onis et al., 2007; de Onis, 2006), and BMI scores for the mothers. Specifically, our analyses utilises maternal BMI measured at child ages 1.5, 4 and 6, and child's BMIz measured at ages 2, 4 and 6.

The GUSTO study collected socioeconomic data from participants at recruitment and again when their children were 5 years old. We coded each mother–child pair as having lower SES (L-SES) if at either recruitment or when their child reached age 5, the mothers reported living in 3 room or smaller public housing flats, and also a household income of approximately under 75% of the national median. This income threshold aligns with the OECD's definition of low-income households (OECD, 2019). As the median household income in Singapore was 5000 Singapore Dollars (SGD) in 2010 and 8292 SGD in 2014 (Department of Statistics, 2010, Department of Statistics 2016), a 75% cut-off would be 3750 SGD and 6219 SGD respectively. However, as GUSTO household income responses were recorded by thousand-dollar bands, the cut-off threshold for lower-income was pegged to $4000 and $6000 at recruitment and Year 5 respectively. In Singapore, 3 room flats (which consists of two bedrooms and range from 60 to 65 square metres) are commonly used as a threshold to identify lower income populations in studies (e.g. Hou, 2019, Malhotra et al., 2013) because residents in such units tend to have lower household incomes than those in larger housing types. A small subset of mothers who did not indicate household income, but who were living in 3 room or smaller public housing units were also classified as 'L-SES'. The rest of the study population is defined as 'higher SES' (H-SES). Our characterisation of L-SES here is based on the assumption that individuals who experience lower socioeconomic status, whether consistently or periodically over time, are substantively different compared to others who consistently maintain a higher socioeconomic status. As a sensitivity analysis, we reran our statistical models using a more restrictive definition of L-SES where participants retained the same SES designation at both baseline and Year 5 (Appendix F).

An important caveat to highlight is that this definition of 'lower SES' covers a spectrum of individuals who are relatively worse off than the rest of the population. Given the relatively small sample size of this study, it is not possible to differentiate the relatively less well-off from the very poor. Additional research beyond this study with a more targeted sample selection will be necessary to study the experiences of the most socioeconomically vulnerable. Similarly, the definition of H-SES here covers a wide range of households, and is not restricted to the substantially high SES per se.

2.2. Neighbourhood level variables

To operationalize neighbourhood 'obesogenicity', we constructed nine accessibility measures of the food environment, active transport environment and active spaces environment for all postal codes in Singapore, where each postal code represents a single address.

While studies measuring accessibility commonly use a 'cumulative opportunities' approach, where features of interest within a specified distance buffer or defined areal unit are counted, such approaches have substantial limitations, which have been well-documented elsewhere. Briefly, one limitation is the simplistic assumption that every location within a defined buffer area shares the same degree of access to the features within the area, even when some locations might be located relatively closer to said features than other locations. A second limitation is the 'edge effect', where a defined buffer area may have no features of interest inside but may have some or more near but outside its boundary which are not counted in the analysis (Talen & Anselin, 1998; Zhang et al., 2011). As an alternative approach that arguably better represents human tendencies to access nearby locations more frequently than further ones, we quantify 'accessibility' to each of the environmental features from each postal code using a 'gravity' metric where features in closer proximity to each location are weighted more highly than features further away. Specifically, we adopt an exponential distance-decay function derived from a previous Singapore-based empirical study of household trips to retail centres (Sevtsuk & Kalvo, 2018). Here, proximity is defined based on shortest path distances along Singapore's road network. We further set a search distance cut-off at 1 km, which approximates a 10 to 15 min walk.

When calculating relative accessibility to each environmental feature of interest, it is important to account for differences in size and/or number of services provided there. For instance, a bus-stop with five bus services provides greater access to public transport services than a bus-stop with only one service. Similarly a small coffee shop with only 10 stalls can cater to fewer diners than a hawker center with hundreds of stalls. In our calculations, we thus weighted the accessibility of each environmental feature by size or estimated number of services, depending on data availability. Appendix B provides details of how each feature is weighted.

Raw accessibility values for the nine measures were first calculated for all postal codes in Singapore. As these raw values had substantially different scales, for ease of analysis and interpretation, we rescored each environmental measure based on quintile values (0 = no feature within search radius, 1 = lowest quintile of accessibility of all postal codes, 5 = highest quintile). We then constructed yearly snapshots of each measure from 2009 to 2017. Using the records of each mother and child's postal code addresses collected during the course of the study, we then calculated their total exposure to each element over the course of the study. For instance, if a mother's records indicated that she lived at a postal code for three years (2010–2012) which had a score of 5 for access to parks, and then lived at a postal code that had a score of 3 for access to parks for the next four years (2013 to 2016), her overall cumulative exposure to parks between 2010 and 2016 would be (3x5 + 4x3)/7.

Table 1 provides an overview of the nine measures, data sources and quintile cut-offs, with more details in Appendix B.

2.3. Statistical analyses

To verify the assumption that there is minimal structural confounding within the GUSTO dataset, we examined whether GUSTO participants' exposures to obesogenic neighbourhood characteristics differed systematically by SES in two ways. First we used frequency tabulations by ethnicity, socioeconomic status, and accumulated exposure to built environment features based on where GUSTO children had lived from birth to age 6. Second, we applied Wilcoxon-Mann-Whitney tests to assess whether there might be significant differences in accumulated exposures by SES category. Details are provided in Appendix D.

To examine how obesogenic neighbourhood characteristics affect risks of childhood obesity, we then fitted a series of regression models of increasing restrictiveness in specifications, using BMI/ BMIz as an outcome. First, we fitted a series of longitudinal fixed effects models controlling for individual and time fixed effects, to analyse how changes in exposure to different obesogenic elements of neighbourhood environment corresponded to changes in maternal BMI scores measured at child ages 1.5, 4 and 6, and child's BMIz measured at ages 2, 4 and 6. Changes in participants' neighbourhood exposures might be due to participants changing residential locations as well as changes in the built environment such as the opening of new public parks or malls. All nine measures of neighbourhood characteristics were included in the statistical models, as some of the variables might be co-occurring: for instance greater exposure to large parks might coincide with more exposure to food outlets that are often included within such parks. To assess possible collinearity, we checked the pair-wise Pearson correlations of participants' year-weighted exposures as of Age 6 (Appendix B).

Even though the proposed longitudinal models are less susceptible to endogeneity than cross-sectional models, they might nevertheless be

Table 1
Characteristics of Obesogenic Neighbourhood Environmental Features.

Overview of Environmental Features, for Year 2017			Quintile Cut-offs of gravity-based accessibility estimates					
Feature	Unit	Source	Q1	Q2	Q3	Q4	Q5	Max
Food Environment								
Grocery stores and fresh food markets	Market Stall or equivalent floor area (13 m^2)	Singapore Food Agency's licensing data	0.37	0.5	0.79	1.3	2.34	29.14
Convenience stores	Store/ Stall	As above	0.37	0.43	0.54	0.78	1.11	4.57
Prepared food outlets	Store/ Stall	As above	0.37	2.81	7	16	38.08	464.6
Unhealthy food outlets[1] relative to all food outlets	Ratio	As above	0	0.09	0.12	0.16	0.22	1
Active Transport								
Bus stops and services	Bus stop, weighted by number of bus services	Land Transport Authority[2]	0.37	6.41	14.08	25.56	45.86	218.8
Rail transit	Station, weighted by number of services	As above	0.07	0.4	0.46	0.57	0.8	4.17
Active Spaces								
Public parks and open spaces	Area (sqm)	URA Master Plan 2014[3]	0.37	20.5	61.96	180.2	545.3	31,381
Park connectors	Length (m)	National Parks Board[3]	0.37	0.96	2.23	4	7.1	28.19
Playgrounds	Playground	National University Singapore	0.37	0.62	0.93	1.62	3.56	17.34

1. Outlets selling fast-food; desserts, fried food etc. Classification method detailed in Appendix B.
2. From LTA's Datamall: https: // datamall.lta.gov.sg/content/datamall/en.html.
3. Data retrieved from data.gov.sg (Urban Redevelopment Authority, 2014).

biased by time-varying confounders. For example, families who developed a greater desire to exercise may over time move to neighbourhoods closer to parks. Families who move might also be doing so because of changes in SES, which might in turn affect their health (Drewnowski et al., 2019). We thus fitted the most restrictive models that examined a specific subset of participants who did not report a change in address from child ages 0 to 6. Restricting the analyses to non-movers allows for an estimation of neighbourhood effects that is unconfounded by residential locational self-selection, since these neighbourhood changes are induced by policies and business decisions beyond the control of the individual parent or child.

To examine how socioeconomic status moderates the neighbourhood effect on obesity, we include an interaction between the variable coding for L-SES and built environment characteristics for the various regression models. A significant interaction effect would suggest that L-SES participants' relationship with the modelled built environment characteristic differs from their H-SES counterparts. Statistical significance was set at $p < 0.05$, for all models.

2.4. Analytical population

We defined three samples of the GUSTO population, each corresponding to different sets of statistical analysis described earlier. For the structural confounding checks, we identified child-mother pairs who provided baseline information about household SES, mothers' ethnicity and geocodeable residential addresses (Sample A, 918 pairs of children and mothers). For the longitudinal analysis, the analytic population consists of a further subset of Sample A who also had at least two BMI measurements between child ages 1.5 and 6. Additionally, we excluded children with BMIz scores at Year 2 that were less than −2, and who could be considered 'wasting' according to the WHO BMI cutoffs, so as to exclude increases in child weight status that should be considered healthy weight gain from our analyses (Sample B 726 children and 669 mothers).

For the most restrictive longitudinal analysis of non-movers, the analytic population consists of a subset of Sample B who did not change residential locations up to Age 6 (Sample C, 320 children and 307 mothers).

3. Results

3.1. Population characteristics

Samples A and B were largely comparable in terms of participants' ethnicity and SES status (See Appendix C). The following descriptive statistics, based on the least restrictive analytic Sample A (n = 918), can thus be taken as representative across these samples.

L-SES mothers made up about 24% (n = 217) of Sample A. In 2010 and 2015, about 17% of Singapore resident households lived in 3 rooms flats or smaller, and had a monthly household income of under SGD 4000, and SGD 6000 respectively, which we classified as 'L-SES' (Census 2010, General Household Survey 2015). The GUSTO sample thus has a slightly larger proportion of L-SES individuals compared to the national population. As summarised in Table 2, L-SES GUSTO mothers were more likely to be single compared to H-SES mothers, of minority ethnicity, and without a university degree. By the time their children reached age 6, L-SES mothers had an average BMI of 26.7– significantly higher than H-SES mothers' 24.5 ($t(230) = 3.87$, p-value < 0.01). The former were also more likely to have obesity than H-SES mothers: 28.3% of L-SES mothers had obesity compared to 18% of H-SES mothers ($\chi 2 = 9.56$, p-value < 0.01). In contrast, there was no statistically significant difference in BMIz scores of children by SES ($t(327)$, p-value = 0.81) nor in obesity rates at age 6 (6.9% for L-SES vs 7.7% for H-SES children, $\chi 2 = 0.06$, p-value = 0.811) In terms of birthweight, L-SES babies weighed slightly less on average, with a mean of3.04 kg for L-SES babies compared to 3.12 kg for H-SES babies ($t(363) = -2.34$, p-value = 0.02).

Table 2
Participants' characteristics by Socioeconomic Status (SES).

Characteristic	Percent of Sample (%)	
	L-SES	H- SES
Marital Status		
Divorced	0	0.1
Married, Living with spouse	88.0	97.6
Married, not living with spouse	0	0.3
Single, living with child's father	2.8	0.9
Single	6.0	0.7
Not Answered.	3.2	0.4
Ethnicity		
Chinese	37.8	60.5
Indian	23	17.3
Malay	39.2	22.3
Education		
A Levels/Poly/Diploma	18.9	26.1
ITE/NITEC	13.8	9.1
Primary	11.1	3.6
Secondary	41.9	20.4
University	13.4	40.8
Data unavailable	0.9	0
Mother's BMI Category[aa] at Year 6 postnatal		
Underweight	2.3	3
Normal	22.1	31.7
Overweight	25.3	22.3
Obese	28.1	18.1
Data unavailable	22.1	25
Child's BMIz Category [b] at Year 6		
Underweight	3.2	2.9
Normal	66.8	63.2
Overweight	9.7	8.1
Obese	6.9	7.7
Data unavailable	13.4	18.1
Total Count	217	701

a: Mother's BMI categories are defined as follows: "Obese" = BMI>=27.5, "Overweight"= BMI>=23, "Underweight" BMI < 18 (HPB, 2016).
b: Child's BMIz categories are defined as follows: "Obese" = +2SD, "Overweight" +1 SD, "Underweight" = −2 SD (de Onis & Lobstein, 2010).

In the same sample, Chinese children and mothers had lower mean BMIz (=-0.16) and BMI scores (23.1) than their Indian (BMIz = 0.09, *t*-test = -1.58, p-value = 0.12; BMI = 27.2, *t*-test = -7.83, p-value < 0.01) and Malay counterparts (BMIz = 0.28, *t*-test = -3.66, p-value < 0.01; BMI = 28.0, *t*-test = -8.98, p-value < 0.01) by the time their children reached age 6.

Examining changes in BMI over time among Sample B GUSTO mothers with repeated readings between year 1.5 to year 6, we find that on average, their BMI increased between year 1.5 to year 6 by 1.13 units. Most stayed within their BMI categories (60%, n = 402), while a good number crossed into a higher BMI category (18%, n = 119), and a smaller proportion crossed into a lower BMI category (4%, n = 25). Sample B GUSTO children saw an average increase of BMIz between year 2 to year 6 by 0.07 units. Similar to GUSTO mothers, most GUSTO children stayed within their BMIz categories (71%, n = 472), a good number crossed into a higher BMI category (19%, n = 126), while some crossed into a lower BMI category (10%, n = 65).

Compared to Samples A and B, the most restrictive Sample C had a slightly smaller proportion of participants classified as L-SES, though not significantly so (about 20% compared to 24%, $\chi 2 = 1.89$, p-value = 0.17), as well as a relatively higher proportion of Chinese participants (64% vs 55%, $\chi 2 = 7.40$, p-value < 0.01). This suggests that the longitudinal analysis of non-movers may over-represent Chinese individuals. Appendix C presents a summary of the comparison between the three samples.

Checks on the structural confounding via frequency tabulations and

Wilcoxon-Mann-Whitney tests suggests minimal evidence of systematic socio-spatial disparities in exposure to obesogenic environments within the GUSTO population (See Appendix D for detailed results).

When examining year-by-year changes in participants' exposures to the nine environmental characteristics, we see exposures to rail stations, park connectors, unhealthy food ratio, and convenience stores increasing somewhat over time, while exposures to bus stops dropped. Comparing movers to non-movers, non-movers on average had a higher exposure over time to most environmental characteristics, with the exception of park connectors and playgrounds. Comparing the relative accessibility scores of the home neighbourhoods of mothers who before and after their first move during the course of the study, we find that movers on average moved to neighbourhoods with less access to bus-stops than their previous neighbourhood: greater access to convenience stores, and less access to food outlets—patterns which might be indicative of preferences guiding neighbourhood selection among movers. (Appendix E provides details).

3.2. Statistical results

Three models were fitted, starting first with a base model which tested only for environmental measures' main effects. The second model included the interaction terms between environmental measures with SES. We then interpret the magnitude and significance of these interaction terms as indicative of differences between H-SES and L-SES mothers' and children's relationship to the environmental measures. As a guard against potential overfitting, a third, more parsimonious model was fitted which kept only the variables with $p < 0.1$ in either the first or second model, together with their respective interaction with SES. The parsimonious third model produced almost exactly the same results as the most comprehensive second model, in terms of significance and magnitude of variables.

3.2.1. Longitudinal analyses: movers and non-movers

Tables 3 and 4 present results from the longitudinal analyses for the combined sample of movers and non-movers, for children and mothers respectively. We find that increased access to bus stops was associated with a decrease in child BMIz (Model 3.2 and 3.3, Table 3).

As all the 'main effects' in the mothers' only models are not statistically significant (Table 4, Models 4.1 to 4.3), these results suggest that for H-SES mothers, changes in environment were not associated with changes in their BMI. Focusing on the parsimonious model 4.3 (Table 4), the 'interaction effects' are significant, which suggest that for L-SES mothers, increased access to convenience stores was associated with increased BMI, while increased access to playgrounds was associated with a reduction in BMI.Changes in exposure to other obesogenic neighbourhood characteristics were not associated with significant changes in BMI.

3.2.2. Longitudinal analyses: non-movers only

Tables 5 and 6 presents results from the longitudinal analyses for the sample of non-movers only, for children and mothers respectively. For children, increased access to park connectors and playgrounds were associated with an increase in BMIz, while for L-SES children specifically, increased access to bus stops were associated with an increase in BMIz compared to their H-SES counterparts where the same change was associated with a decrease in BMIz. Increased access to rail stations were also associated with a decrease in L-SES children's BMIz (Model 5.2 and 5.3, Table 5).

For GUSTO mothers, the H-SES mothers saw a decrease in BMI when their access to park connectors increased, whereas conversely L-SES mothers saw an increase in their BMI. One unit increase in year-weighted exposure to park-connectors was associated with a widening between the H-SES and L-SES mothers' BMI of 0.45 units. Changes in exposure to other neighbourhood characteristics were not associated with significant BMI changes (Model 6.2, Table 6).

Table 3
Longitudinal Analysis: Movers and Non-movers, Child BMIz and Environmental Changes between Age 2 & 6.

	(Model 3.1)	(Model 3.2)	(Model E.3.3)
	Coef (95% CI)	Coef (95%CI)	Coef (95%CI)
Unhealthy Food Ratio	−0.03 (−0.15, 0.08)	0.01 (−0.13, 0.14)	
Fresh Produce	−0.05 (−0.17, 0.06)	−0.11 (−0.25, 0.03)	
Convenience Stores	−0.01 (−0.08, 0.07)	−0.04 (−0.13, 0.05)	
All Food Outlets	0.19* (0.02, 0.36)	0.19~ (−0.01, 0.40)	0.12 (−0.04, 0.28)
Rail Stations	−0.07 (−0.18, 0.04)	−0.06 (−0.19, 0.07)	
Bus Stops	−0.09 (−0.23, 0.06)	−0.17* (−0.33, −0.002)	−0.18* (−0.34, −0.02)
Parks, Open Space, Sports	0.04 (−0.08, 0.16)	0.07 (−0.06, 0.21)	0.10 (−0.02, 0.23)
Playgrounds	−0.04 (−0.16, 0.08)	0.004 (−0.14, 0.15)	
Park Connectors	0.04 (−0.04, 0.13)	0.08 (−0.03, 0.18)	
L-SES:Unhealthy Food Ratio		−0.15 (−0.39, 0.10)	
L-SES:Fresh Produce		0.15 (−0.10, 0.40)	
L-SES:Convenience Stores		0.09 (−0.06, 0.24)	
L-SES:All Food Outlets		0.04 (−0.35, 0.43)	0.02 (−0.29, 0.34)
L-SES:Rail Stations		−0.03 (−0.27, 0.22)	
L-SES:Bus Stops		0.25 (−0.06, 0.57)	0.24 (−0.07, 0.55)
L-SES:Parks, Open Space, Sports		−0.26~ (−0.55, 0.03)	−0.24~ (−0.50, 0.03)
L-SES:Playgrounds		−0.16 (−0.44, 0.11)	
L-SES:Park Connectors		−0.05 (−0.24, 0.14)	
Observations	2,064	2,064	2,064
R^2	0.01	0.02	0.01

Note: ~ $p < 0.1$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

4. Discussion

This study found empirical support for the hypotheses that socio-economic status modified the relationship between exposure to specific obesogenic neighbourhood characteristics and BMI-related outcomes. Specifically, the most methodologically stringent 'non-movers only' longitudinal models found that increased access over time to purportedly 'healthy' park connectors was associated with a decrease in BMI outcomes for H-SES mothers, but an increase for L-SES mothers. Similar to L-SES mothers, these models also found increased access to park connectors to be associated with increased child BMIz.

Studies, mostly in North America, have found that women and lower-income individuals were more fearful of crime in urban green spaces in their neighbourhoods than men and higher income individuals, which impeded their use of such spaces for leisure and physical activity (Cohen et al., 2016; Sreetheran & van den Bosch, 2014), and which might partially explain how such amenities affect high and low SES groups differently. It is debateable whether this explanation might apply to Singapore, given that Singapore has very low crime rates and there is currently no evidence or data suggesting that parks, park connectors or other recreational facilities in lower-income neighbourhoods differ in quality, perceived safety or actual crime rates, from higher-income ones.

Table 4
Longitudinal Analysis: Movers and Non-movers, Mother BMI and Environmental Changes between Age 2 & 6.

	(Model 4.1)	(Model 4.2)	(Model 4.3)
	Coef (95%CI)	Coef (95%CI)	Coef (95%CI)
Unhealthy Food Ratio	0.01 (−0.25, 0.26)	−0.07 (−0.37, 0.24)	
Fresh Produce	−0.01 (−0.26, 0.24)	−0.08 (−0.37, 0.21)	
Convenience Stores	0.11 (−0.06, 0.27)	−0.02 (−0.21, 0.17)	−0.05 (−0.23, 0.13)
All Food Outlets	−0.14 (−0.52, 0.24)	−0.09 (−0.53, 0.35)	
Rail Stations	0.16 (−0.09, 0.40)	0.09 (−0.21, 0.39)	
Bus Stops	−0.03 (−0.34, 0.28)	0.06 (−0.29, 0.41)	
Parks, Open Space, Sports	0.13 (−0.13, 0.39)	0.14 (−0.16, 0.43)	
Playgrounds	0.08 (−0.18, 0.33)	0.23 (−0.07, 0.53)	0.17 (−0.11, 0.46)
Park Connectors	−0.08 (−0.27, 0.11)	−0.16 (−0.39, 0.07)	
L-SES: Unhealthy Food Ratio		0.17 (−0.38, 0.73)	
L-SES: Fresh Produce		0.07 (−0.47, 0.62)	
L-SES: Convenience Stores		0.49** (0.17, 0.82)	0.57*** (0.26, 0.88)
L-SES: All Food Outlets		0.19 (−0.72, 1.11)	
L-SES: Rail Stations		0.24 (−0.30, 0.78)	
L-SES: Bus Stops		−0.33 (−1.05, 0.39)	
L-SES: Parks, Open Space, Sports		−0.05 (−0.66, 0.56)	
L-SES: Playgrounds		−0.62* (−1.21, −0.03)	−0.52* (−1.03, −0.02)
L-SES: Park Connectors		0.35 (−0.07, 0.77)	
Observations	1,808	1,808	1,808
R^2	0.01	0.02	0.02

Note: ~ $p < 0.1$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table 5
Longitudinal analysis: non-movers only, Child BMIz and Environmental Changes between Age 2 & 6.

	(Model 5.1) Coef (95%CI)	(Model 5.2) Coef (95%CI)	(Model 5.3) Coef (95%CI)
Unhealthy Food Ratio	0.13 (−0.08, 0.33)	0.15 (−0.08, 0.37)	
Fresh Produce	−0.16 (−0.50, 0.18)	−0.15 (−0.57, 0.27)	
Convenience Stores	0.01 (−0.11, 0.13)	0.05 (−0.08, 0.18)	
All Food Outlets	0.23 (−0.27, 0.72)	0.27 (−0.26, 0.79)	
Rail Stations	0.04 (−0.33, 0.42)	0.41 (−0.11, 0.93)	0.46~ (−0.05, 0.98)
Bus Stops	−0.22 (−0.55, 0.11)	−0.49* (−0.87, −0.11)	−0.46* (−0.82, −0.10)
Parks, Open Space, Sports	0.14 (−0.59, 0.86)	0.21 (−0.54, 0.95)	
Playgrounds	0.83 (−0.48, 2.15)	1.46~ (−0.05, 2.96)	1.60* (0.11, 3.09)
Park Connectors	0.23* (0.004, 0.46)	0.34* (0.04, 0.63)	0.38** (0.09, 0.66)
L-SES:Unhealthy Food Ratio		−0.11 (−0.63, 0.42)	
L-SES:Fresh Produce		−0.01 (−0.73, 0.70)	
L-SES:Convenience Stores		−0.03 (−0.28, 0.22)	
L-SES:All Food Outlets		−0.69 (−2.45, 1.08)	
L-SES:Rail Stations		−0.67~ (−1.43, 0.09)	−0.75* (−1.49, −0.01)
L-SES:Bus Stops		1.12** (0.32, 1.92)	1.02** (0.27, 1.77)
L-SES:Parks, Open Space, Sports		−1.24 (−4.55, 2.07)	
L-SES:Playgrounds		−1.85 (−5.43, 1.73)	−2.44 (−5.48, 0.60)
L-SES:Park Connectors		−0.29 (−0.76, 0.18)	−0.37 (−0.83, 0.08)
Individual FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	918	918	918
R^2	0.02	0.04	0.03

Note:~ $p < 0.1$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Nevertheless, several Singapore-based studies found that some Singaporeans perceived a lack of safety around their neighbourhood parks and park connectors, which reduced their desire to visit said spaces (Uijtdewilligen et al., 2019; Yuen et al., 1999; Yuen, 1996). Furthermore, other Singapore-based studies and surveys have found that women had more concerns about crime and security than men, as did individuals of lower SES compared to those of higher SES (Mathews et al., 2021; Yeoh & Yeow, 1997).

Alternatively, this counter-intuitive finding might be due to some other environmental change that coincided with the opening up of new park connectors within one's neighbourhood, other than the ones already measured and accounted for in this study. Additional research into how individuals and families might be perceiving and interacting with park connectors around their homes is important and necessary to establish any causal mechanisms at play. Our findings here suggest urban interventions that seek to reduce obesity risks by building more park connectors require more careful study, to avoid only benefiting higher SES groups and exacerbating existing inequalities.

The non-mover models also found that increased access to bus stops was associated with an increase in BMIz for L-SES children, but conversely a decrease in BMIz for H-SES children. As lower SES individuals are less likely to own cars and instead rely more on cheaper modes such as walking and public transport than more well-off counterparts, (Basu & Ferreira, 2020; Tan & Samsudin, 2017; Singstat, 2016), they may potentially substitute walking for more passive bus travel in response to new bus stops opening. A 2016 paper examining changes in total walking and physical activity of a sample of Los Angeles residents after the opening of new light rail stations found that participants living within half mile of a new station who already had high walking and physical activity levels at baseline experienced a reduction in physical activity after the opening of a new station (Hong et al., 2016). Similarly, a 2015 study of Utah residents before and after the completion of light rail stations found that users already using public transit before the new stations and who continued doing so reported, on average, a slight increase in BMI and slight decrease in physical activity (Brown et al., 2015). Interestingly, increased access to rail stations was associated with a decrease in BMIz of L-SES children only, which suggests that relationships between child BMIz and environment may differ by type of public transport infrastructure. A tentative explanation is that L-SES children may be more likely to walk to rail stations than H-SES counterparts. Since rail stations are more spaced out in provision than bus stops and thus on average require more walking to reach (Olszewski & Wibowo, 2000), the physical activity accrued through rail station use would be more than through bus stop use. However, as there have been no Singapore-specific empirical studies that examine how changes in public transport provision might affect physical activity behaviours, and how these effects differ by SES, the above explanations are at best tentative. More research tracking physical activity changes before and after the introduction of new public transport infrastructure, and which examines how these might differ by baseline travel mode and socio-economic status would be necessary to verify this tentative explanation.

Interestingly, the significant relationship between changes in bus

Table 6
Longitudinal Analysis: Non-movers only, Mothers' BMI and Environmental Changes between Age 2 & 6.

	Outcome: Mother BMI		
	(Model 6.1)	(Model 6.2)	(Model 6.3)
	Coef (95%CI)	Coef (95%CI)	Coef (95%CI)
Unhealthy Food Ratio	0.15 (−0.27, 0.57)	0.14 (−0.32, 0.61)	
Fresh Produce	0.20 (−0.43, 0.83)	0.33 (−0.44, 1.10)	
Convenience Stores	−0.03 (−0.26, 0.20)	−0.08 (−0.34, 0.18)	
All Food Outlets	−0.81~ (−1.75, 0.13)	−0.65 (−1.65, 0.34)	
Rail Stations	0.08 (−0.61, 0.77)	−0.11 (−1.09, 0.88)	
Bus Stops	−0.04 (−0.69, 0.62)	0.16 (−0.59, 0.92)	
Parks, Open Space, Sports	−0.13 (−1.97, 1.71)	0.03 (−1.92, 1.99)	
Playgrounds	2.66* (0.24, 5.09)	1.63 (−1.17, 4.43)	1.82 (−0.88, 4.51)
Park Connectors	−0.24 (−0.67, 0.20)	−0.62* (−1.18, −0.07)	−0.64* (−1.18, −0.11)
L-SES: Unhealthy Food Ratio		0.09 (−0.95, 1.14)	
L-SES: Fresh Produce		−0.38 (−1.78, 1.01)	
L-SES: Convenience Stores		0.13 (−0.33, 0.59)	
L-SES: All Food Outlets		−2.17 (−5.62, 1.29)	
L-SES: Rail Stations		0.23 (−1.17, 1.64)	
L-SES: Bus Stops		−0.69 (−2.22, 0.84)	
L-SES: Parks, Open Space, Sports		−0.35 (−6.23, 5.53)	
L-SES: Playgrounds		7.34* (0.71, 13.97)	3.90 (−1.50, 9.31)
L-SES: Park Connectors		1.15** (0.28, 2.02)	1.09* (0.24, 1.93)
Observations	838	838	838
R^2	0.02	0.04	0.03

Note: ~ $p < 0.1$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

and rail infrastructure and BMI was observed only for GUSTO children, which suggest they might be more responsive to this particular change than their mothers. As the maximum age of GUSTO children for this particular study was six years old, they were unlikely to be travelling independently from their caretakers. However, even if mothers and children changed their behaviours similarly, children may be more sensitive to the same amount of walking substitution because the energy expended to walk a fixed distance or at a given speed is substantially greater for smaller individuals compared to larger individuals (DeJaeger et al., 2001; Weyand et al., 2010).

4.1. Difference between movers and Non-movers

Comparing results from the two sets of longitudinal analyses suggest that individuals who moved to new locations responded differently to changes in their built environment, compared to those who experienced in-situ changes. The movers and non-mover models found that for L-SES mothers, increased access to convenience stores was associated with increased BMI, and while increased access to playgrounds was associated with a reduction in BMI. One potential explanation is that women of lower SES who prioritised access to convenience stores and to playgrounds might have deliberately relocated to neighbourhoods with better access to these features, and thus were more likely to change their behaviours accordingly after moving. In contrast, those who stayed in the same location might not similarly prioritise these features, and may thus be less sensitive to increased exposure to these elements. This possibility of differing preferences guiding the residential neighbourhood selection choices of movers compared to non-movers is broadly supported by our observation of significant differences between movers and non-movers' neighbourhood environmental exposures, as well as tendency of movers to relocate to neighbourhoods of certain characteristics (Appendix E).

Another possible explanation is that relocations served as 'shocks' that broke old habits of travel or consumption (Verplanken et al., 2008; Walker et al., 2015) in ways that more gradual change in neighbourhood characteristics might not (Drewnowski et al., 2019). This reasoning could be applied to explain why the 'movers and non-movers' models found that for L-SES mothers, increased access to convenience stores to be significantly associated with an increase in BMI, and increased access to playgrounds to be significantly associated with a decrease in BMI, whereas the 'non-movers only' models found these associations to be insignificant.

For GUSTO mothers, while the 'non-movers' models found that higher SES mothers' BMI decreased with increased access to park connectors while lower SES mothers' BMI increased, this relationship was not observed in the 'movers and non-movers' model. For GUSTO children, the 'non-movers' models found that increase in access to bus stops was associated with a decrease in BMIz of H-SES children and a sizeable increase in BMIz of L-SES children, while increased access to park connectors and playgrounds were associated with BMIz increase, regardless of SES. However, the 'movers and non-movers' model found increased bus access to be associated with a small reduction in children's BMIz overall, and that increased access to park connectors had no discernible effect. These divergent findings might be due to confounding from changes in circumstances that drove the relocation (Drewnowski et al., 2019; Morris et al., 2018). Furthermore, those who moved would have had to contend with multiple changes at once (Morris et al., 2018), potentially complicating the relationship between neighbourhood characteristics, and health.

Given the lack of comparable studies that might help verify how residential mobility might modify neighbourhood effects, the explanations offered above for the differences observed between movers and non-movers are necessarily tentative. Findings from this study thus reinforce the call for more research into how residential relocation, and its triggers, might interact with neighbourhood effects, in order to understand the complex ways people interact with their environments to produce different health outcomes (Morris et al., 2018).

4.2. Differences between mothers and children

The longitudinal models suggested that the same neighbourhood characteristics affect mothers and children differently. For instance, changes in exposure to convenience stores and playgrounds affected only mothers' BMI, whereas changes in bus stop access affected only children's BMIz, for movers and non-movers. This observation supports theories that neighbourhood effects on obesity change over one's life course (Hawkins et al., 2018), which have hitherto been relatively under-studied using empirical data. While studies often report different associations between neighbourhood exposures and obesity-related outcomes by age (Jia et al., 2019), most focus on age-stratification within bounded age categories, rather than across a span of age groups. Longitudinal studies also tend to focus on relatively short periods of time (Alvarado, 2016) which precludes the ability to compare adult and child outcomes. To date, there have been only two studies looking at how adults and children's obesity-related outcomes might be differently affected by similar neighbourhood characteristics (Saelens et al., 2012; Van Hulst et al., 2013). This study thus adds to this sparse empirical field.

4.3. Limitations

As only home locations were available for GUSTO participants, this study focuses solely on the influence of residential environments, which is limiting because other environments around workplaces and schools could also expose individuals to obesogenic influences. Certain potentially important environmental characteristics could not be tested due to data limitations. For instance, the lack of fine-grained, historical food prices information made it impossible to incorporate considerations of food costs. This study also focuses primarily on physical built environment characteristics, and is not able to account for any place-based policies or initiatives that might encourage or hinder physical activity or healthy eating.

Furthermore, given the small subpopulation of 'lower SES' mother–child pairs, this study's ability to identify smaller neighbourhood and SES interaction effects was limited. The relatively small sample size also precluded our ability to examine how participants of very high SES might differ from other more moderately well-off individuals.

Additionally, as income and housing type information was only collected at two time points (recruitment and Year 5), this study was not able to explicitly account for changes in participants' SES at any other time points during the course of the study. Some of the links between neighbourhood environmental change and BMI change might therefore be confounded by uncaptured SES changes. Furthermore, this study does not focus on how different changes in socioeconomic status might affect obesity risks, because our sample, particularly the non-movers, has only few participants with certain types of changes in socioeconomic status (e.g. only 8 out of 307 non-mover GUSTO mothers logged a shift from higher SES at recruitment to lower SES at Year 5). Our small sample size thus precludes the ability to adequately study the relationship between different changes in SES status, environmental change and BMI/ BMIz.

Another limitation of our study is that we focus primarily on the outcome of adult BMI and child BMIz, There are however many alternative measures of obesity risks that are not covered within this study. For instance, the age at which a child undergoes adiposity rebound, which refers to the second rise in body mass index that occurs between 3 and 7 years, is a potentially interesting measure since an early age at adiposity rebound is known to be a risk factor for later obesity (Cole, 2004, Kang, 2018). While a detailed examination of adiposity rebound effect and how it relates to SES and environmental exposures is currently out of scope for our study, this is an area this is an area could that be investigated in future studies.

Finally, as this study focuses solely on BMI and BMIz rather than actual behavioural responses, such as changes in mode of transport in response to infrastructural changes, changes in physical activity in response to new parks and park connectors, or changes in mother and child diet quality in response to changes in the food environment, the hypothesised explanations for the observed relationships that hinge on behaviour change are largely speculative. While this study is one of the first attempts to examine individual BMI outcomes in relation to environmental conditions in Singapore, there is a need for more empirical research to verify these hypothesised causal pathways.

5. Conclusion

Using more robust, longitudinal methods of analysis, our study has identified some specific neighbourhood interventions that could potentially mitigate obesity risks and generated findings suggesting that neighbourhood environments affect obesity risks in a wealthy, high-density Asian city like Singapore in similar ways as hitherto more studied 'Western' contexts, even though there are cultural, lifestyle and built environment differences between the urban contexts. This study also underscores the importance of considering how socioeconomic status can modify one's relationship with the same built environment. Policy-makers should carefully consider how urban interventions can be tailored to meet the specific needs of individuals of lower SES, bearing in mind how time and financial resource constraints might affect behaviours, choice sets, knowledge and beliefs, and not assume that simply adding 'healthful' infrastructure would suffice. Additional efforts to address these fundamental differences in resources, behaviours and knowledge would be necessary to complement built environmental changes.

Finally, this study highlights the limits of solely relying on built environment interventions to address obesity disparities. Even though Singapore presents an integrated urban environment, there are still clear disparities in women's obesity rates by SES observed in this and several other Singapore- based studies (Malhotra et al., 2013; Park et al., 2020; Sabanayagam et al., 2007; Sabanayagam et al., 2007; Wang et al., 2016). The low 'within-person' R-squared measures across the longitudinal fixed-effects models also suggests that relatively little of the variation in BMIz or BMI was explained by changes in neighbourhood environmental variables. That neighbourhood factors account for a relatively small proportion of variation in individual health outcomes, compared to individual-level, family-level, or peer-group level factors, has been well-established elsewhere (Diez Roux, 2001; Sellstrm & Bremberg, 2006). Nevertheless, given that changes to the urban environment can affect a very large population over a long period of time, even a relatively small degree of improvement can be substantial, and should be pursued when possible. It is important to continue pursuing spatial strategies to reduce obesity-related disparities, while supporting efforts to understand and address other fundamental, modifiable causes that might be driving such health disparities between socioeconomic groups.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2022.104450.

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