THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Could strength of exposure to the residential neighbourhood modify associations between walkability and physical activity?

Citation for published version:
Ivory, V, Blakely, T, Pearce, J, Witten, K, Bagheri, N, Badland, H & Schofield, G 2015, 'Could strength of exposure to the residential neighbourhood modify associations between walkability and physical activity?' Social Science & Medicine, vol. 147, pp. 232-241. DOI: doi:10.1016/j.socscimed.2015.10.053

Digital Object Identifier (DOI):
doi:10.1016/j.socscimed.2015.10.053

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Social Science & Medicine

Could strength of exposure to the residential neighbourhood modify associations between walkability and physical activity?

Ivory V, Blakely T, Pearce J, Witten K, Bagheri N, Badland H, Schofield G.

Social Science & Medicine

Abstract

The importance of neighbourhoods for health and wellbeing may vary according to an individual's reliance on their local resources, but this assertion is rarely tested. We investigate whether greater neighbourhood 'exposure' through reliance on or engagement with the residential setting magnifies neighbourhood-health associations.

Methods: Three built environment characteristics (destination density, streetscape (attractiveness of built environment) and street connectivity) and two physical activity components (weekday and weekend accelerometer counts) were measured for 2033 residents living in 48 neighbourhoods within four New Zealand cities in 2009-2010, giving six different built environment – physical activity associations. Interactions for each built environment – physical activity association with four individual-level characteristics (acting as proxies for exposure: gender, working status, car access, and income) were assessed with multi-level regression models; a total of 24 'tests'.

Results: Of the 12 weekday built environment – physical activity tests, 5 interaction terms were significant ($p<0.05$) in the expected direction (e.g. stronger streetscape-physical activity among those with restricted car access). For weekend tests, one association was statistically significant. No significant tests were contradictory. Pooled across the 12 weekday physical activity 'tests', a 1 standard deviation increase in the walkability of the built environment was associated with an overall 3.8% (95% CI: 3.6% to 4.1%) greater increase in weekday physical activity across all the types of people we hypothesised to spend more time in their residential neighbourhood, and for weekend physical activity it was 4.2% (95% CI 3.9% to 4.5%).

Conclusions: Using multiple evaluation methods, interactions were in line with our hypothesis, with a stronger association seen for proxy exposure indicators (for example, restricted car access). Added to the wider evidence base, our study strengthens causal evidence of an effect of the built environment on physical activity, and highlights that health gains from improvements of the residential neighbourhood may be greater for some people.

Keywords: Physical activity, built environment, effect modification, multilevel modelling, walkability, New Zealand

Introduction:

Residential neighbourhoods are one setting where people are exposed to environmental characteristics thought to influence health behaviours (Ball et al., 2006; Chaix, 2009). Yet different ways of living and mobility across different settings for work, recreation, and education (among other activities) means people will engage with different types of environments in their everyday life (Shareck et al., 2014), as well as their residential environment. Could certain individual factors affect the way people engage with and are therefore exposed to the residential environment? If so, could these individual factors modify the neighbourhood-health relationship (Diez Roux & Mair, 2010; Shareck et al., 2014)? Addressing such questions is important for furthering our understanding of the causal nature of a relationship between residential neighbourhoods and health practices such as physical activity, but researchers face considerable challenges (Ball et al., 2006). The aim of this paper is to test the 'exposure' hypothesis by using theory-driven effect modification methods to investigate variation in the association of the residential neighbourhood built environment with physical activity by selected individual factors.

A rapidly increasing international body of work is establishing robust evidence for an association between neighbourhood built environments and residents' level of physical activity. Residents of neighbourhoods characterised as more 'walkable', aesthetically attractive, and with a range of destinations tend to have higher levels of physical activity [Anonymous 2012d]. Such associations remain even after accounting for potential confounding factors such as income, education, neighbourhood deprivation, and importantly, personal preference for neighbourhood type [Anonymous 2012a], adding to the case for a causal relationship. A further test of causality would be determining whether such an association were stronger among those with a greater level of exposure to local built environment factors (Daniel et al., 2008). Greater exposure could hypothetically be due to mechanisms such as more time spent in the residential built environment compared to others and the nature of the activities that occur in different environments (Kwan, 2009); through greater reliance on or preference for local environments and amenities (Chaix, 2009; Perchoux et al., 2014; Shareck et al., 2014) [Anonymous, 2015], as well as the intensity of relationships to people and places within the local setting (McCreanor et al., 2006)[Anonymous, 2015].

Variation by strength of exposure to environmental characteristics is not only of public health interest as it shows who may benefit the most from the neighbourhood built environment and how the built environment may narrow/widen health inequalities [Anonymous 2011c](Shareck et al., 2014), but is also a test of specificity about the (presumed) causal association. The absence of such variation could suggest residual confounding or other systematic error that is spuriously producing an association when there is no true relationship. Physical activity may be a useful test of neighbourhood exposure mechanisms because it is built into the daily routines of residents, and therefore likely to be responsive to the current residential characteristics (Van Dyck et al., 2011) over and above preferences and practices accumulated over the life course (Cockerham, 2005). If so, we would expect to see a stronger relationship between the neighbourhood residential built environment and physical activity for those with a higher level of exposure to their neighbourhood.

People engage with multiple environments as they go about their daily life (Ball et al., 2006; Chaix et al., 2012; Hurvitz & Moudon, 2012; Matthews, 2008; Perchoux et al., 2014; Shareck et al., 2014), potentially leading to differences in the strength of their 'exposure' to the residential environment (Daniel et al., 2008; Shareck et al., 2014). Empirical evidence of differential exposure includes stronger neighbourhood-health associations for people with restricted car access (Inagami et al., 2009) and women (Kavanagh et al., 2006)[Anonymous 2011a]. Reasons why differential exposure could lead to stronger neighbourhood health 'effects' (Perchoux et al., 2014)could occur in a variety of ways. The amount of time spent in the local neighbourhood relative to other geographical settings has been shown through 'activity space' studies that use geographic positioning systems (GPS) to measure the location and timing of movements within and beyond residential neighbourhoods. Findings show time spent in local settings to be higher for those who are not in the paid labour force and/or lower income (Perchoux et al., 2014), restricted mobility (for example through limited car access) (Chaix et al., 2012; Shareck et al., 2014), and longer term residents (Chaix et al., 2009; Vallée et al., 2011), and women (Kestens et al., 2012; Kwan, 1999; Perchoux et al., 2014). Several mechanisms have been put forward to explain why these factors might lead to 'exposure' effects. Greater mobility afforded by ready car access or high income may provide opportunities for residents to select and engage in activities outside of their neighbourhood (Diez Roux, 2003; Eriksson et al., 2012; Manaugh & El-Geneidy, 2011; Perchoux et al., 2014). Low income or reduced access to a car can act as a restraint to travelling further afield, restricting everyday activities such as shopping or leisure to mainly local facilities (Bostock, 2001; Cleland et al., 2010), potentially leading to cycles of entrapment in less healthy environments (Shareck et al., 2014; Smith & Easterlow, 2005). Explanations for gender differences in activity space and stronger neighbourhood-health associations include women's greater role in household responsibilities (Perchoux et al., 2014) and child-rearing (Kavanagh et al., 2006), and through gendered ways of interacting with social networks and place (Matheson et al., 2006)[Anonymous 2011a] [Anonymous 2015] (Kavanagh et al., 2006)

If some residents are less engaged with, or spend less time in, their residential neighbourhood because, for example, they work full time elsewhere or have the resources to travel widely, the built environment characteristics of these other significant places (such as paid employment locations) could plausibly also influence their physical activity levels. Presumably then, the characteristics of the residential setting may have relatively less influence on physical activity for these more mobile people. Conversely, whose everyday activities are geographically constrained could have greater dependence on (and arguably exposure to) local resources and environments (Perchoux et al., 2014; Vallée et al., 2011). While the above studies have demonstrated how individual factors could interact with neighbourhood characteristics to influence health outcomes, or identified variation in activity space patterns, to our knowledge, no studies have systematically and statistically compared a range of 'exposure' factors for their interaction with the built environment-physical activity relationship.

Observing effect modification in the built environment-physical activity association can therefore provide insights into how place-health relations vary amongst different socio-demographic groups, and the degree to which reliance on local resources might differ. The presence of statistical interactions between individual factors, the residential neighbourhood built environment, and individual physical activity could suggest synergistic or buffering processes (Diez Roux & Mair, 2010; Ding et al., 2012), including differential exposure to the neighbourhood setting (Inagami et al., 2007)[Anonymous 2011c]. For example, living in a neighbourhood with plentiful informal opportunities for being physically active (such as walking or cycling) might buffer residents against the impact of limited individual or household means to take part in costly organised sports or gym membership.

A few studies of the built environment and physical activity have provided results that are stratified by factors that could act as proxies of daily neighbourhood 'exposure'. While some have examined variation in the built environment/physical activity association by individual characteristics (Forsyth et al., 2009; Kerr et al., 2007; McCormack et al., 2014; Pan et al., 2009), a noticeable feature is their diversity in study samples, population sub-groups being examined, and measures of the built environment and physical activity, which makes interpretation of the often contradictory findings more difficult. On one hand Kerr et al's study (2007) of self-reported walking behaviours of adolescents observed weaker associations between built environment and physical activity among 'white' compared with 'non-white' populations. Forsyth et al (2009) on the other hand found little difference by ethnicity with respect to self-reported physical activity but did report a stronger association between the built environment and accelerometer-measured physical activity among adult residents classified as 'non-white' compared to 'white'. Neither study further explored the differences in the associations statistically, for example by using effect measure modification techniques.

Pan et al (2009) identified statistical interactions between individual and residential neighbourhood built environment factors, then applied post-hoc stratified modelling only where interactions were statistically significant. They observed a stronger association between the neighbourhood level of amenities and self-reported physical activity for men (whereas Kerr et al (2007) found adolescent females had stronger association between commercial land use measures and walking than males), and for those with university qualifications. In Manaugh and El-Geneidy's (2011) study of household walking practices, wealthy car owners were shown to be more responsive to neighbourhood walkability than low income households. McCormack et al (2014) found the opposite, with the difference in levels of (self-reported) neighbourhood-based physical activity between low and high walkable neighbourhoods being smaller for participants from lower income households (but with overlapping confidence intervals). However, robust inferences about the results were limited due to very small numbers of participants in the most walkable neighbourhoods. Aside from differences between studies in measurement and analytical methods, a notable limitation of these studies is the limited specification of hypothesised mechanisms (Diez Roux & Mair, 2010) leading to uncertainty for why, for example, heterogeneity in the associations would exist between 'white and 'non-white' residents, and in what direction? In contrast to this earlier work, Eriksson et al (2012) both hypothesised that vehicle ownership would modify the built environment-physical activity association, with non-car owners more sensitive to the built environment, and then statistically tested for effect modification; however they found no evidence of statistical interaction between vehicle ownership and the built environment with moderate to vigorous physical activity (Eriksson et al., 2012).

In previous New Zealand work, the relationship between neighbourhood built environment and individual-level physical activity was assessed using five neighbourhood-level exposures (street connectivity, dwelling density, land use mix, destination density, and streetscape). Analyses were adjusted for potential confounders at the individual level (age, gender, income, education, car access, employment and preference for neighbourhood walkability) and for neighbourhood level deprivation. Aspects of the built environment (particularly destination density, street connectivity, and dwelling density) contributed to both self-reported and objectively measured physical activity in adults [Anonymous 2012b]., Accounting for neighbourhood deprivation resulted in stronger associations; an important step as New Zealand neighbourhoods ranked as relatively deprived tend to have better street connectivity, and greater dwelling density and access to destinations.

To further our understanding of how neighbourhood environments come to affect health behaviours such as physical activity we now undertake a novel study approach using effect measure modification techniques to statistically explore variation in the built environment – physical activity association. We take advantage of comprehensive survey data that included information on four individual characteristics identified in the above literature that could plausibly act as proxy indicators for the strength of exposure to the local neighbourhood – that is, we used them as potential modifying factors. Drawing on the literature discussed above, the hypothesis is that people who are more 'exposed', and potentially more reliant on, their neighbourhood and potentially more reliant on it (in our study, those not in fulltime paid work, women, restricted car access, and lower income) would have stronger associations between the built environment and physical activity than those less exposed (i.e. in fulltime paid work, men, full car access, higher income). Finally, it was also hypothesised that more interactions (in the expected direction) would be found for weekday physical activity if exposure is primarily a factor of time, assuming traditional weekly working schedules.

Methods:

Sample: Forty eight neighbourhoods were selected across four cities in New Zealand (Waitakere, North Shore (now amalgamated into the single city of Auckland)), Wellington, and Christchurch). Neighbourhoods were selected to provide contrast in 'walkability'. Over 2009/2010, a total sample of 2,033 adult residents aged 20-65 years were recruited, 42 from each study neighbourhood, using a strategy designed to obtain a representative sample. As well as collecting objective measures of physical activity (see below) participants took part in a face-to-face survey that collected information on physical activity and a wide range of individual and household factors, including labour force status, location of paid employment, ease of access to a motor vehicle, income levels, and so on. The study response rate was 44.81% [Anonymous 2012b].

Three measures of the built environment were used in this paper to represent different dimensions of the built environment. Street connectivity (intersection density) was generated using Geographic Information Systems (GIS), according to International Physical Activity and Environment Network (IPEN) research protocols [Anonymous 2009]. The index was calculated at the meshblock level (the smallest administrative geographic unit used by Statistics New Zealand of approximately 100 people) and then combined at the neighbourhood level. Five or more contiguous meshblocks with similar built environment characteristics comprised a single study neighbourhood, with the score derived from the mean meshblock values. Detailed descriptions of the methodology are provided elsewhere [Anonymous 2009].

The safety and aesthetic qualities of the study neighbourhood streetscape were measured using the systematic audit tool, Systematic Pedestrian and Cycling Environment Scan (SPACES) (Pikora et al., 2003), modified for use in New Zealand [Anonymous 2010]. Scores of 12 randomly selected street segments within the study neighbourhood were combined to give a neighbourhood SPACES score. The GIS-based Neighbourhood Destinations Accessibility Index (NDAI) [Anonymous 2011d] measured the density of eight domains of community services and destinations (education, transport, recreation, social and cultural, food retail, financial, health, and other retail) within walking distance (an 800m buffer along the road network from the population-weighted centroid) of each study neighbourhood (for more details see [Anonymous 2011d]). The built environment measures were statistically rescaled by dividing by their standard deviations to aid comparisons across exposures.

Objective measures of physical activity were obtained using hip-mounted Actical accelerometers for seven consecutive days. We used the mean number of accelerometer counts per hour of wear-time separated by weekday and weekend periods and weighted by wear time (John et al., 2010; Kerr et al., 2013). Non-wear was categorised as periods of >59 minutes with consecutive zero counts with zeros set to missing; and periods of <60 minutes during which the accelerometer was worn (in case participants only wore the accelerometer to exercise). (De Bourdeaudhuij et al., 2003). To reduce the potential bias arising from the exclusion of less compliant participants we included accelerometer data for all complete hours of daily wear , based on the above criteria (for further details see [Anonymous 2012b]). To accommodate skewed outcome data, we used natural log of accelerometer counts in the analysis.

Effect modifiers and covariates: Four variables were selected as potential effect modifiers with levels representing degrees of 'exposure' to the neighbourhood environment (italics representing greater hypothesised 'exposure'); paid working status (working fulltime outside of the neighbourhood (based on provided workplace address information) / *not working fulltime*), gender (men / *women*), car access (full access to use of a car / *restricted use or no access to a car*) and income (higher household income ≥ NZ$60,000 (the median income band in the survey started at $60,001)/ *lower household income < NZ$60,000*). Also included as confounders were factors previously established as confounders to the built environment-physical activity association [Anonymous, 2012]: individual-level age, marital status, education attainment, ethnicity, and a neighbourhood measure of deprivation (NZDep06 (Salmond et al., 2007) a small-area (meshblock) measure developed using 2006 census data on socioeconomic characteristics (means tested benefits, employment, equivalised household income, access to a telephone, access to a car, single parent family, qualifications, home ownership, household overcrowding)).

Analysis: Bivariate relationships between weekday and weekend physical activity and exposure to the built environment measures were examined across covariates for our sample. Relationships between the built environment exposure variables (categorised as tertiles for ease of comparison) and covariates are summarised in Supplementary Table 1.

Evidence of effect measure modification was undertaken in four stages. Firstly, multilevel linear regression analyses were used to mutually adjust for individual and neighbourhood characteristics, and for clustering within neighbourhoods (that is, a main effects model). Analyses were conducted separately for each built environment measure for observations with complete data. By using the natural log of accelerometer counts as the outcome variable, and built environment variables divided by their standard deviation, the exponent of the built environment coefficient is the ratio, or relative (percentage) change in the outcome measure for each one standard deviation change in the neighbourhood built environment exposure. Thus it is possible to compare results across built environment exposures, and across the weekday and weekend physical activity outcome measures.

Next, fully adjusted regressions were first run, stratified by each potential effect modifier. Then interaction terms between the built environment exposure and the potential effect modifier (e.g., NDAI*gender) were added to the main effects model, adjusting for the *a priori* confounders and for other modifiers (where they may also play a confounding role). Thirdly, interaction term estimates and Wald tests of the estimates were reviewed for statistical significance. Finally, pooled estimates were averaged for the 12 interaction terms (three built environment characteristics by four individual-level characteristics) for weekday physical activity, and likewise for the 12 weekend physical activity interaction terms. This was done by taking the exponent of the average beta coefficient (from the log-link regressions) for the interaction terms across all 12 interaction models, with variance equal to the sum of the 12 variances divided by 12 squared.

Built environment – physical activity estimates from the stratified and interaction term analyses were reviewed for their magnitude, direction, and statistical significance. In addition to considering each potential modifier separately, patterns across the 24 analyses were reviewed for their consistency with the hypothesis using tabular and graphical formats. We used this 'pattern ascertainment' as a qualitative means of mitigating the risks due to the limited power of interaction testing to find 'true interactions' (type II error), but also that by chance some interactions will be found (type I error). That is, it would be erroneous to place too much emphasis on just one or two statistically significant interactions out of a battery of many tests as one or two statistically significant interactions would be expected by chance alone.

Analyses were completed in Stata (version 11.2; StataCorp LP, College Station, TX, USA) over 2011- 2012.

Ethical approval was granted by [Details omitted for double-blind reviewing] ethics committees. Informed consent was obtained from all participants.

Results:

There was variability in the distribution of the sample population by the various covariates and built environment exposures (Supplementary Table 1). The strongest relationships between the built environment characteristics with individual-level covariates were seen for household income and car access; for example, 47% of those with restricted car access lived in the most connected street network areas, compared with only 28% of those with full car access. Weaker relationships were seen for streetscape. Minimal variability was seen in the distribution of the sample across built environment tertiles for gender and working status, and they were therefore not included as potential confounders in the main effects analyses.

Physical activity varied across covariates (Table 1). With regard to weekday physical activity, men, 30-34 year olds, non-Māori, those with school qualifications, never married, paid working full time, higher income, restricted car access, or living in the most deprived areas (relatively) had the highest levels of physical activity. By comparison, those with the highest levels of weekend physical activity were 55-65 years, tertiary qualified, or living in relatively less deprived areas.

Main effect: multilevel regressions adjusted for confounders. After adjustment for individual confounders and neighbourhood deprivation, NDAI and street connectivity were both associated with increased levels of weekday and weekend physical activity (Supplementary Table 2), consistent with the associations reported elsewhere [Anonymous, 2012b]). For each standard deviation change in the NDAI and street connectivity exposures, weekday physical activity increased by 7% (1.07 (95% CI: 1.03-1.12)); with a slightly smaller (6%) increase for weekend physical activity for NDAI and an 8% increase for weekend physical activity for street connectivity. A smaller increase was seen for physical activity with respect to streetscape, and confidence intervals included the null (weekday: 1.03 (95% CI: 0.99-1.08); weekend 1.02 (95% CI: 0.98-1.07)).

Effect measure modification analyses: The pattern of results across the stratified (Figure 1) and interaction analyses (Figure 2, Table 1) provide some support for statistical interaction between individual characteristics and built environment measures, notably for car access and household income. Stratified analyses are presented graphically in Figure 1:a-d, illustrating variability in the magnitude of the association between the built environment measures and physical activity. Figure 2 presents the magnitude of each interaction term parameter graphically for weekday (2a) and weekend (2b); each bar represents the difference in the built environment-physical activity gradient for individuals who may be more exposed to the neighbourhood environment compared with their less exposed complement. For example, the parameter estimates for street connectivity*car access (1.10 (95% CI; 1.02-1.18)) suggest that the built environment-physical activity gradient is 10% greater for those with restricted car access. For further details, Table 2 presents full results with the interaction term estimates with 95% confidence intervals and accompanying Wald test *p* values.

For *weekday* physical activity (Figure 2a), five of the 12 interactions terms were significant ($p<0.05$) in the expected direction (e.g. stronger streetscape-physical activity among residents not working fulltime), 7 non-significant, and none significant in the non-hypothesised direction. Pooled across the 12 weekday physical activity 'tests', a 1 standard deviation increase in the overall walkability of the built environment was associated with an overall 3.8% (95% CI: 3.6% to 4.1%) greater increase in weekday physical activity across all the types of people we hypothesised to spend more time in their residential neighbourhood.

For *weekend* physical activity (Figure 2b) only one of the 12 interaction terms was significant (street connectivity*car access, p=0.013), and 11 were non-significant. Nevertheless, the bars in Figure 1b are all 'to the right' in support of the hypothesis. Further, when pooled across the 12 weekend physical activity 'tests', a 1 standard deviation increase in the built environment measure was associated with a 4.2% (95% CI 3.9% to 4.5%) greater increase in weekend physical activity across all hypothetically more 'exposed' residents. This pooled weekend estimate is not that different from the weekday estimate in magnitude (4.2% versus 3.8%), but has a slightly wider confidence interval due to covering only two days of physical activity compared with five – and is consistent with the wider confidence intervals in Figure 2b compared with Figure 2a.

Discussion

We observed variation in the magnitude of association of the neighbourhood built environment (street connectivity, neighbourhood destinations and streetscape) and objectively measured physical activity. Evidence of statistical interactions was stronger for lower household income and restricted car access but less so for employment status and gender, after accounting for potential individual and neighbourhood confounding factors. When viewed overall, the pattern of heterogeneity was consistent with our *a priori* expectation that the physical activity levels of residents who may be thought of as more exposed to the residential neighbourhood would be more strongly associated with its built environment features. These findings demonstrate the importance of considering how neighbourhood effects on health could be intensified for some residents, with implications for health inequalities (Shareck et al., 2014).

Our analytical approach used multiple evaluation methods to assess the presence of theorised interactions. Three different measures of built environment, four proxies of neighbourhood exposure, and two periods of physical activity were tested, a total of 24 individual analyses. While a risk of using multiple combinations is that positive findings could be found by chance alone, the interaction terms of six analyses were statistically significant at the 5% level – mostly for the statistically more powerful weekday physical activity analyses. As importantly, the direction of the interaction term estimates in 20 out of 24 analyses supported the hypothesis with the remaining four analyses having relatively small or null estimates. On balance, stronger interactions for weekday physical activity compared to weekend physical activity were not found, just more statistically precise estimates. Using a combination of methods moved us on from reliance on stratified analyses or interaction tests alone, and helped us work around the statistical power limitations typically seen in multilevel studies.

The nature of the heterogeneity we saw supports the case that there will be interactions between individual factors and the neighbourhood-health relationship (Diez Roux & Mair, 2010). More specifically, the pattern of variability supports the hypothesis that more 'exposure' to the residential neighbourhood setting may intensify the built environment-physical activity associations in some groups, which is in turn what could be expected if there was a causal relationship between the built environment and physical activity. For example, our findings showed that the built environment-physical activity gradients were steeper across income and car access groups compared to gender and working status. One explanation is that these groups are more responsive to their local neighbourhood environments (Perchoux et al., 2014; Shareck et al., 2014; Stafford & Marmot, 2003) because lower income and car access act to constrain where they go in daily life - their "real life spatial trajectories" (Chaix, 2009, p. 94). This may be even more so in New Zealand where low density urbanism is the norm and where it may be more logistically difficult to use public transport or more expensive in the short term (Bostock, 2001; Cleland et al., 2010).

While there appears to be some differences in the strength of association across groups, there is little to suggest that some population groups in our study were 'immune' to neighbourhood factors, in contrast to findings elsewhere (Forsyth et al., 2009). That is, for residents categorised as relatively less 'exposed', at least one aspect of the neighbourhood built environment was still associated with increased levels of physical activity across the built environment gradient (Figure 1:a-d). For example, the built environment estimates in the NDAI*car access interaction analyses (Table 3) represent the NDAI-physical activity association in the hypothetically 'less exposed' strata who have ready access to a car, indicating a 6% relative increase in physical activity across the built environment gradient.

Limitations:

Differences in the estimates between strata were generally small, and confidence intervals overlapped, reflecting the small effect size and imprecision of these data. A lack of variation of individual characteristics in our sample may have limited the ability to observe statistically significant interactions (Diez Roux & Mair, 2010), leading to an underestimation of synergies between individual 'exposure' and built environment in some of the 'tests'. However, the analytical approach was designed to reduce reliance on statistical tests for variation alone, and to instead interpret the nature of the heterogeneity based on the *a priori* expectations.

The study was limited to using indicators of car access, employment status, household income, and gender which we used as proxies for the strength of 'exposure' to the neighbourhood environment. But to what extent do these indicators represent actual differences in how residents are exposed to or engage with their local neighbourhood? Those not in paid work outside of their neighbourhood may not necessarily spend more time in the residential neighbourhood if key activities are located elsewhere (e.g. recreational activity, caregiver activities). Access to a car does not equate to use but may make it more likely for residents to drive elsewhere and allow people to be less reliant on their local neighbourhood. Therefore it is feasible that some non-differential misclassification of the proxies occurred. All other things being equal, a consequence is that the magnitude of true variation by actual level of daily 'exposure' to residential neighbourhoods may have been underestimated.

Contrary to the hypothesis, we did not see notable differences in the evidence for effect modification between weekday and weekend activity once statistical precision was considered. That is, working status mattered across the whole week, not just when adults were working. One interpretation is that 'exposure' represents how people interact more broadly with the residential built environment, not just daily mobility or time spent locally [Anonymous, 2015]. In part, this could be because physical activity levels also represent local, socially informed 'collective lifestyles' where people both influence and are influenced by their neighbourhood (Frohlich & Potvin, 1999), not just individual behavioural responses to the built environment. Secondly, physical activity practices within residential settings may be carried through into other environments resulting in residents being more or less active overall. For example, if it is the norm for residents in a given neighbourhood to walk or cycle to their local shops, they may also use active transport modes more readily outside of their neighbourhood, such as for commuting to work. Thirdly, residential environments are the daily starting point for journeys throughout the day, and are therefore likely to provide important parameters for how and where residents relate to and use local *and* non-local physical activity resources (Chaix et al., 2012).

Because the study uses objectively measured physical activity it does not distinguish between forms of activity by domains (transport, work or leisure), limiting comparisons with studies using recreational-, occupational-, or transport-related outcomes. An important advantage of using the objective accelerometer-based measures, however, is that the physical activity measure is less subject to under- or over-reporting by demographic groups [Anonymous, 2011b]. Further, this study uses accelerometer counts which may better capture a broader range of everyday 'incidental' physical activity practices that may be more influenced by neighbourhood settings, such as walking to the corner shop, restricting to than just moderate-to-vigorous-physical activity measures. Nonetheless, it is likely that some types of physical activity may show more heterogeneity than others, and could therefore be more amenable to interventions at both area and targeted population group levels.

Another limitation of our cross sectional observational study is the potential for selection bias either from non-participation or partial participation. Selection bias is more likely if participation were low in the complete case analyses however the weekday N was 81% and weekend N was 76% of the total sample. It is unlikely that the built environment – physical activity association would be so different and so large amongst the people who partially participated that it would result in the 'true' association being substantially changed.

The moderate response rate (44.81%) also raises selection bias concerns. Again, for bias to have occurred in this study, a strongly negative association would need to be present for non-participants, such that living in a highly walkable neighbourhood was associated with much lower activity levels. While such patterns are always possible, we think it unlikely it would be sufficiently strong to reverse the observed associations.

Finally, our study does not distinguish between activity undertaken in the residential neighbourhood and elsewhere. Studies measuring activity space are increasingly being used to capture an individual's total environmental exposure (Chaix et al., 2012; LeDoux & Vojnovic, 2013; Perchoux et al., 2013), and more recently, how individual factors predict the scale of activity space (Perchoux et al., 2014). Such studies have been instrumental in helping research avoid the 'local trap' where studies reflect only residential neighbourhood scales when thinking about the environment (Cummins, 2007). However, we also need to understand more about the significance of residential factors for physical activity. The study reported by Perchoux et al (2014) was based in an inner city location with relatively homogenous urban form, meaning they were not able to observe whether the type of neighbourhood itself (as well as individual characteristics) could be a factor in how far people travel. A complementary social practice approach has been to look at how different residents from varying types of neighbourhoods actively manage or construct the opportunities for being physically active in their everyday lives. In this study, women and those not in fulltime employment talked about being active in public places in more regular and intimate ways when compared with men, those in full time employment, and those in neighbourhoods with fewer opportunities for physical activity. Neighbourhood walkability factors combined with individual factors such as employment shape how people engage with their neighbourhood [Anonymous, 2015], supporting the nature of statistical interactions reported in this paper.

Of substantive interest for future work is whether 'exposure' is simply a matter of time spent in the residential locality (say when compared with work-based neighbourhoods with different environmental characteristics (Inagami et al., 2009; Inagami et al., 2007)), or a function of more comprehensive engagement with or reliance on the local neighbourhood setting (Wood et al., 2010). Addressing such place-based questions are likely to require studies incorporating GPS technology into accelerometers to map the location of everyday activity across local and non-local areas, as well as observational and reported data on how and why people move in and out of local residential areas, and whether that differs by individual *and* neighbourhood factors. To truly inform the role of place in the neighbourhood-health relationship however, they will also need to assess how such physical activity-related mobility matters for the nature of engagement in more or less healthy neighbourhoods [Anonymous, 2015], and ultimately the implications for a range of health outcomes.

Increasing our knowledge of the causal nature of the built environment-physical activity relationship can best be achieved through the careful interpretation of the totality of evidence and careful evaluation of tested hypotheses. While difficult (Diez Roux & Mair, 2010), investigating interactions between the neighbourhood and individual factors can challenge simplistic understandings of neighbourhood effects, question extant assumptions and concepts (such as residence equating to equal exposure to the neighbourhood), and lead to more refined theory and hypothesising. In this paper, conducting analyses to test the 'exposure' hypothesis allows examination of *why* residential neighbourhood effects are unlikely to be homogeneous across populations, leading to a more nuanced understanding of how residential neighbourhoods get 'under the skin' through everyday practices such as physical activity.

Conclusion:

The results presented here add support to the wider evidence base for a true causal association between the built environment and physical activity. In general, residential neighbourhood built environment characteristics were related to physical activity engagement to some degree for all the population groups observed. However, the extent to which residential neighbourhood environments structure health behaviours such as physical activity may vary according to individual factors, notably ones that may be proxies for the strength of daily exposure to the neighbourhood through higher levels of engagement with and reliance on the residential environment. From a public health perspective, such findings point to the benefits of intervening in the built environment of places to ensure that local employment, goods and services are sufficient so people are not doubly disadvantaged by limited personal, household, *and* neighbourhood resources (Jack, 2006). Our findings reinforce the need to consider synergies between where people live *and* who they are when thinking about the role of the neighbourhood for living healthy active lives.

References

[Anonymous, 2012a] Details omitted for double-blind reviewing

[Anonymous, 2010] Details omitted for double-blind reviewing

[Anonymous, 2009] Details omitted for double-blind reviewing

[Anonymous, 2011a] Details omitted for double-blind reviewing

[Anonymous, 2015] Details omitted for double-blind reviewing

[Anonymous, 2011b] Details omitted for double-blind reviewing

[Anonymous, 2011c] Details omitted for double-blind reviewing

[Anonymous, 2012b] Details omitted for double-blind reviewing

[Anonymous, 2011d] Details omitted for double-blind reviewing

Ball, K., Timperio, A.F., & Crawford, D.A. (2006). Understanding environmental influences on nutrition and physical activity behaviors: Where should we look and what should we count? *International Journal of Behavioral Nutrition and Physical Activity,* 3.

Bostock, L. (2001). Pathways of disadvantage? Walking as a mode of transport among low-income mothers. *Health & Social Care in the Community,* 9, 11.

Chaix, B. (2009). Geographic life environments and coronary heart disease: A literature review, theoretical contributions, methodological updates, and a research agenda. *Annual Review of Public Health,* 30, 81-105.

Chaix, B., Kestens, Y., Perchoux, C., Karusisi, N., Merlo, J., & Labadi, K. (2012). An Interactive Mapping Tool to Assess Individual Mobility Patterns in Neighborhood Studies. *American Journal of Preventive Medicine,* 43, 440-450.

Chaix, B., Merlo, J., Evans, D., Leal, C., & Havard, S. (2009). Neighbourhoods in eco-epidemiologic research: Delimiting personal exposure areas. A response to Riva, Gauvin, Apparicio and Brodeur. *Social Science & Medicine,* 69, 1306-1310.

Cleland, V., Ball, K., Hume, C., Timperio, A., King, A.C., & Crawford, D. (2010). Individual, social and environmental correlates of physical activity among women living in socioeconomically disadvantaged neighbourhoods. *Social Science & Medicine,* 70, 2011-2018.

Cockerham, W.C. (2005). Health lifestyle theory and the convergence of agency and structure. *Journal of Health and Social Behavior,* 46, 51-67.

Cummins, S. (2007). Commentary: Investigating neighbourhood effects on health--avoiding the 'Local Trap'. *International Journal of Epidemiology,* 36, 355-357.

Daniel, M., Moore, S., & Kestens, Y. (2008). Framing the biosocial pathways underlying associations between place and cardiometabolic disease. *Health & Place,* 14, 117-132.

De Bourdeaudhuij, I., Sallis, J.F., & Saelens, B.E. (2003). Environmental correlates of physical activity in a sample of Belgian adults. *American Journal of Health Promotion,* 18, 83-92.

Diez Roux, A.V. (2003). Residential Environments and Cardiovascular Risk. *Journal of Urban Health,* 80, 569-589.

Diez Roux, A.V., & Mair, C. (2010). Neighborhoods and health. *Annals of the New York Academy of Sciences,* 1186, 125-145.

Ding, D., Sallis, J.F., Conway, T.L., Saelens, B.E., Frank, L.D., Cain, K.L., et al. (2012). Interactive effects of built environment and psychosocial attributes on physical activity: A test of ecological models. *Annals of Behavioral Medicine,* 44, 365-374.

Eriksson, U., Arvidsson, D., Gebel, K., Ohlsson, H., & Sundquist, K. (2012). Walkability parameters, active transportation and objective physical activity: moderating and mediating effects of motor vehicle ownership in a cross-sectional study. *International Journal of Behavioral Nutrition and Physical Activity,* 9, 123.

Forsyth, A., Michael Oakes, J., Lee, B., & Schmitz, K.H. (2009). The built environment, walking, and physical activity: Is the environment more important to some people than others? *Transportation Research Part D: Transport and Environment,* 14, 42-49.

Frohlich, K.L., & Potvin, L. (1999). Collective lifestyles as the target for health promotion. *Canadian Journal of Public Health,* 90.

Hurvitz, P.M., & Moudon, A.V. (2012). Home Versus Nonhome Neighborhood: Quantifying Differences in Exposure to the Built Environment. *American Journal of Preventive Medicine,* 42, 411-417.

Inagami, S., Cohen, D.A., Brown, A.F., & Asch, S.M. (2009). Body mass index, neighborhood fast food and restaurant concentration, and car ownership. *Journal of Urban Health,* 86, 683-695.

Inagami, S., Cohen, D.A., & Finch, B.K. (2007). Non-residential neighborhood exposures suppress neighborhood effects on self-rated health. *Social Science and Medicine,* 65, 1779-1791.

Jack, G. (2006). The area and community components of children's well-being. *Children and Society*, 20, 334-347.
John, D., Tyo, B., & Bassett, D.R. (2010). Comparison of four actigraph accelerometers during walking and running. *Medicine and Science in Sports and Exercise,* 42, 368-374.
Kavanagh, A.M., Bentley, R., Turrell, G., Broom, D.H., & Subramanian, S.V. (2006). Does gender modify associations between self rated health and the social and economic characteristics of local environments? *J Epidemiol Community Health,* 60, 490-495.
Kerr, J., Frank, L., Sallis, J.F., & Chapman, J. (2007). Urban form correlates of pedestrian travel in youth: Differences by gender, race-ethnicity and household attributes. *Transportation Research Part D: Transport and Environment,* 12, 177-182.
Kerr, J., Sallis, J.F., Owen, N., De Bourdeaudhuij, I., Cerin, E., Sugiyama, T., et al. (2013). Advancing science and policy through a coordinated international study of physical activity and built environments: IPEN adult methods. *Journal of Physical Activity and Health,* 10, 581-601.
Kestens, Y., Lebel, A., Chaix, B., Clary, C., Daniel, M., Pampalon, R., et al. (2012). Association between activity space exposure to food establishments and individual risk of overweight. *PLoS One,* 7.
Kwan, M.P. (1999). Gender and Individual Access to Urban Opportunities: A Study Using Space–Time Measures. *The Professional Geographer,* 51, 210-227.
Kwan, M.P. (2009). From place-based to people-based exposure measures. *Social Science and Medicine,* 69, 1311-1313.
LeDoux, T.F., & Vojnovic, I. (2013). Going outside the neighborhood: The shopping patterns and adaptations of disadvantaged consumers living in the lower eastside neighborhoods of Detroit, Michigan. *Health & Place,* 19, 1-14.
Manaugh, K., & El-Geneidy, A. (2011). Validating walkability indices: How do different households respond to the walkability of their neighborhood? *Transportation Research Part D: Transport and Environment,* 16, 309-315.
Matheson, F.I., Moineddin, R., Dunn, J.R., Creatore, M.I., Gozdyra, P., & Glazier, R.H. (2006). Urban neighborhoods, chronic stress, gender and depression. *Social Science and Medicine,* 63, 2604-2616.
Matthews, S.A. (2008). The Salience of Neighborhood: Some Lessons from Sociology. *American Journal of Preventive Medicine,* 34, 257-259.
McCormack, G.R., Shiell, A., Doyle-Baker, P.K., Friedenreich, C.M., & Sandalack, B.A. (2014). Subpopulation differences in the association between neighborhood urban form and neighborhood-based physical activity. *Health and Place,* 28, 109-115.
McCreanor, T., Penney , L., Jensen, V., Witten, K., Robin, K., & Moewaka Barnes, H. (2006). 'This is like my comfort zone': Senses of place and belonging within Oruamo/Beachhaven, New Zealand. *New Zealand Geographer,* 62, 196-207.

Pan, S., Cameron, C., DesMeules, M., Morrison, H., Craig, C., & Jiang, X. (2009). Individual, social, environmental, and physical environmental correlates with physical activity among Canadians: a cross-sectional study. *BMC Public Health,* 9, 21.

Perchoux, C., Chaix, B., Cummins, S., & Kestens, Y. (2013). Conceptualization and measurement of environmental exposure in epidemiology: Accounting for activity space related to daily mobility. *Health and Place,* 21, 86-93.

Perchoux, C., Kestens, Y., Thomas, F., Hulst, A.V., Thierry, B., & Chaix, B. (2014). Assessing patterns of spatial behavior in health studies: Their socio-demographic determinants and associations with transportation modes (the RECORD Cohort Study). *Social Science and Medicine,* 119, 64-73.

Pikora, T., Giles-Corti, B., Bull, F., Jamrozik, K., & Donovan, R. (2003). Developing a framework for assessment of the environmental determinants of walking and cycling. *Social Science & Medicine,* 56, 1693-1703.

Salmond, C., Crampton, P., & Atkinson, J. (2007). NZDep2006 Index of Deprivation. Wellington: Department of Public Health, University of Otago.

Shareck, M., Kestens, Y., & Frohlich, K.L. (2014). Moving beyond the residential neighborhood to explore social inequalities in exposure to area-level disadvantage: Results from the Interdisciplinary Study on Inequalities in Smoking. *Social Science and Medicine,* 108, 106-114.

Smith, S.J., & Easterlow, D. (2005). The strange geography of health inequalities. *Transactions of the Institute of British Geographers,* 30, 173-190.

Stafford, M., & Marmot, M. (2003). Neighbourhood deprivation and health: does it affect us all equally? *Int J Epidemiol,* 32, 357-366.

Vallée, J., Cadot, E., Roustit, C., Parizot, I., & Chauvin, P. (2011). The role of daily mobility in mental health inequalities: The interactive influence of activity space and neighbourhood of residence on depression. *Social Science & Medicine,* 73, 1133-1144.

Van Dyck, D., Cardon, G., Deforche, B., Owen, N., & De Bourdeaudhuij, I. (2011). Relationships between neighborhood walkability and adults' physical activity: How important is residential self-selection? *Health & Place,* 17, 1011-1014.

Wood, L., Frank, L.D., & Giles-Corti, B. (2010). Sense of Community and its relationship with walking and neighborhood design. *Social Science & Medicine,* 70, 1381-1390.

Appendix

Supplementary Table 1: Study sample stratified by covariates and built environment exposures

			Built environment exposures								
			Streetscape n (%)			**Neighbourhood Destination Access Index n (%)**			**Street connectivity n (%)**		
Covariates		*Total n(%)*	*Tertile 1 (least supportive)*	*Tertile 2*	*Tertile 3 (most supportive)*	*Tertile 1 (least destinations)*	*Tertile 2*	*Tertile 3 (most destinations)*	*Tertile 1 (least connected)*	*Tertile 2*	*Tertile 3 (most connected)*
Gender	*Men*	853 (42)	290 (34)	279 (33)	284 (33)	303 (35)	285 (33)	265 (31)	284 (33)	292 (34)	277 (32)
	Women	1179 (58)	399 (34)	394 (33)	386 (33)	415 (35)	394 (33)	370 (31)	394 (33)	423 (36)	362 (31)
Age (years)	*20-29*	450 (22)	231 (51)	135 (30)	84 (19)	167 (37)	161 (36)	122 (27)	161 (36)	147 (33)	142 (31)
	30-34	780 (39)	236 (30)	262 (34)	282 (36)	273 (35)	261 (33)	246 (31)	258 (33)	283 (36)	239 (31)
	45-54	464 (23)	133 (29)	163 (35)	168 (36)	159 (34)	150 (32)	155 (34)	158 (34)	152 (33)	154 (33)
	55-65	327 (16)	87 (37)	111 (34)	129 (39)	113 (35)	105 (32)	109 (33)	95 (29)	130 (40)	102 (31)
Ethnicity	*Māori*	241 (12)	99 (41)	89 (37)	53 (22)	93 (38)	96 (40)	52 (22)	76 (31)	98 (41)	67 (28)
	Non-Māori	1792 (88)	591 (33)	584 (33)	617 (34)	625 (35)	584 (32)	583 (32)	603 (34)	617 (34)	572 (32)
Education attainment	*No qualifications*	546 (27)	190 (35)	207 (38)	149 (27)	204 (37)	221 (40)	121 (22)	164 (30)	242 (44)	140 (26)
	School qualifications	234 (12)	71 (30)	64 (27)	99 (42)	76 (32)	65 (28)	93 (40)	76 (32)	70 (30)	88 (38)

	Trade or diploma	474 (23)	155 (33)	159 (33)	160 (34)	171 (36)	162 (34)	141 (30)	148 (31)	190 (40)	136 (29)
	University	771 (38)	269 (35)	241 (31)	261 (34)	266 (35)	232 (30)	273 (35)	290 (38)	211 (27)	270 (35)
Marital status	*Never married*	447 (22)	128 (29)	158 (35)	161 (36)	111 (25)	144 (32)	192 (43))	94 (21)	158 (34)	199 (45)
	married	1302 (64)	469 (36)	419 (32)	414 (32)	513 (40)	432 (33)	357 (27)	502 (38)	452 (35)	348 (27)
	Previously married	279 (14)	89 (32)	96 (34)	94 (34)	91 (33)	103 (37)	85 (30)	80 (29)	108 (39)	91 (32)
NZ index of Deprivation 2006	*Quintile 1 (least deprived)*	419 (20)	126 (30)	37 (9)	256 (61)	293 (70)	84 (20)	42 (10)	335 (80)	42 (10)	42 (10)
	Quintile 2	423 (21)	127 (30)	254 (60)	42 (10)	168 (40)	126 (30)	129 (30)	168 (40)	126 (30)	129 (30)
	Quintile 3	380 (19)	87 (23)	129 (34)	164 (43)	44 (11)	170 (45)	166 (44)	47 (12)	208 (55)	125 (33)
	Quintile 4	430 (21)	218 (51)	127 (29)	85 (20)	171 (40)	90 (21)	129 (34)	129 (30)	127 (30)	174 (40)
	Quintile 5 (most deprived)	381 (19)	132 (35)	126 (33)	123 (32)	42 (11)	210 (55)	129 (34)	0 (0.0)	212 (56)	169 (44)
Working status	*fulltime*	1182 (58)	404 (34)	402 (34)	376 (32)	412 (35)	394 (33)	376 (32)	396 (33)	408 (34)	378 (32)
	not fulltime	848 (42)	284 (33)	271 (32)	293 (35)	305 (36)	284 (33)	259 (30)	282 (33)	307 (36)	259 (30)
Household Income ($NZ)	*>$60,001*	1088 (60)	393 (36)	343 (32)	352 (32)	419 (38)	349 (32)	320 (29)	428 (39)	329 (30)	331 (30)
	<$60,000	737 (40)	218 (30)	273 (37)	246 (33)	216 (29)	276 (37)	245 (33)	171 (23)	321 (43)	245 (33)

Car access	*Full access*	1661 (82)	560 (34)	562 (34)	539 (32)	617 (37)	567 (34)	477 (29)	589 (35)	606 (36)	466 (28)
	Restricted or no access	371 (18)	130 (35)	111 (30)	130 (35)	100 (27)	113 (30)	158 (43)	89 (24)	109 (29)	173 (47)

NDAI, Neighbourhood Destination Access Index
NZDep, NZ index of Deprivation 2006

Supplementary Table 2: Relative change in physical activity for a one standard deviation change in neighbourhood exposure: main effects models

Exposures		***Streetscape***		***NDAI***		***Street Connectivity***	
	Relative change in accelerometer count per hour	**Weekday**	**Weekend**	**Weekday**	**Weekend**	**Weekday**	**Weekend**
		N=1641	**N=1536**	**N=1641**	**N=1536**	**N=1641**	**N=1536**
Built environment		1.03 (0.99-1.08)	1.02 (0.98-1.07)	*1.07 (1.03-1.12)*	*1.06 (1.01-1.11)*	1.07 (1.03-1.12)	1.08 (1.03-1.13)
Age	*15-29*	1.00 (0.93-1.07)	0.99 (0.91-1.08)	1.00 (0.93-1.07)	0.99 (0.91-1.07)	1.00 (0.93-1.07)	0.99 (0.91-1.07)
	30-44	1.00	1.00	1.00	1.00	1.00	1.00
	45-54	0.98 (0.92-1.05)	0.98 (0.91-1.07)	0.98 (0.92-1.05)	0.98 (0.91-1.07)	0.98 (0.92-1.05)	0.98 (0.91-1.07)
	55-65	0.97 (0.90-1.05)	1.03 (0.94-1.14)	0.98 (0.90-1.05)	1.03 (0.94-1.14)	0.97 (0.90-1.05)	1.03 (0.94-1.13)
Education attainment	*No Qualification*	1.06 (0.99-1.14)	1.01 (0.93-1.10)	1.07 (1.00-1.15)	1.02 (0.93-1.11)	1.07 (0.99-1.15)	1.02 (0.93-1.11)
	School	1.02 (0.93-1.11)	1.01 (0.90-1.12)	1.02 (0.93-1.11)	1.01 (0.90 -1.12)	1.02 (0.94-1.12)	1.01 (0.91-1.12)
	Trade or diploma	1.05 (0.98-1.12)	0.96 (0.89-1.05)	1.05 (0.98-1.13)	0.96 (0.89-1.05)	1.05 (0.98-1.13)	0.96 (0.89-1.05)
	University	1.00	1.00	1.00	1.00	1.00	1.00
Marital status	*Never married*	1.05 (0.98-1.13)	0.99 (0.91-1.08)	1.05 (0.98-1.13)	0.99 (0.91-1.08)	1.05 (0.98-1.13)	0.99 (0.90-1.08)
	Married	1.00	1.00	1.00	1.00	1.00	1.00
	Previous married	0.91 (0.84-0.99)	0.93 (0.85-1.03)	0.91 (0.84-0.99)	0.93 (0.85-1.03)	0.91 (0.84-0.98)	0.93 (0.84-1.02)
NZDep06 quintiles	*1 Least deprived*	1.00	1.00	1.00	1.00	1.00	1.00
	2	0.98 (0.87-1.10)	0.90 (0.79-1.03)	0.95 (0.85-1.06)	0.88 (0.77-1.01)	0.92 (0.82-1.03)	0.85 (0.75-0.96)
	3	0.95 (0.84-1.08)	0.92 (0.80-1.06)	0.91 (0.81-1.03)	0.89 (0.78-1.03)	0.90 (0.80-1.01)	0.86 (0.76-0.98)
	4	0.93 (0.82-1.05)	0.88 (0.77-1.01)	0.85 (0.75-0.96)	0.83 (0.72-0.95)	0.85 (0.75-0.96)	0.80 (0.70-0.92)

	5 Most deprived	0.96 (0.84-1.10)	0.79 (0.67-0.92)	0.89 (0.78-1.02)	0.74 (0.63-0.87)	0.88 (0.77-1.01)	0.72 (0.62-0.83)
Ethnicity	*Non-Māori*	1.00	1.00	1.00	1.00	1.00	1.00
	Māori	1.00 (0.92-1.08)	0.89 (0.80-0.98)	1.00 (0.92-1.09)	0.89 (0.80-0.99)	1.00 (0.92-1.08)	0.89 (0.80-0.98)
Household Income ($NZ)	*>$60,001*	1.00	1.00	1.00	1.00	1.00	1.00
	<$60,000	0.99 (0.93-1.05)	0.89 (0.83-0.96)	0.99 (0.93-1.06)	0.90 (0.83-0.97)	0.99 (0.93-1.06)	0.90 (0.83-0.97)
Car access	*Full access*	1.00	1.00	1.00	1.00	1.00	1.00
	Restricted or no access	1.04 (0.97-1.12)	1.05 (0.96-1.14)	1.04 (0.97-1.12)	1.05 (0.96-1.14)	1.04 (0.96-1.12)	1.04 (0.95-1.14)

NDAI, Neighbourhood Destination Access Index

NZDep, NZ index of Deprivation 2006

Figure Captions

Figure 1:a-d: Built environment and physical activity associations stratified by gender, working status, car access and income

Figure 2:a-b: Statistical interactions between the built environment, physical activity, and gender, working status, car access and income; weekday and weekend

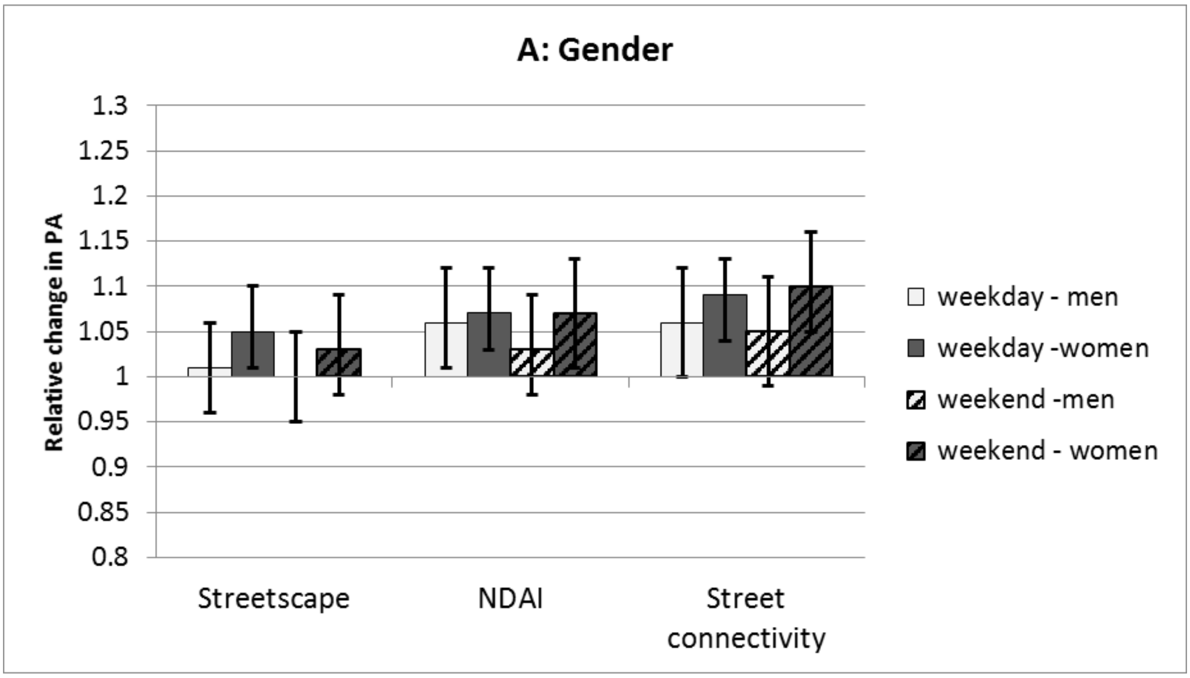
Table 1: Variation in physical activity by built environment exposures and covariates

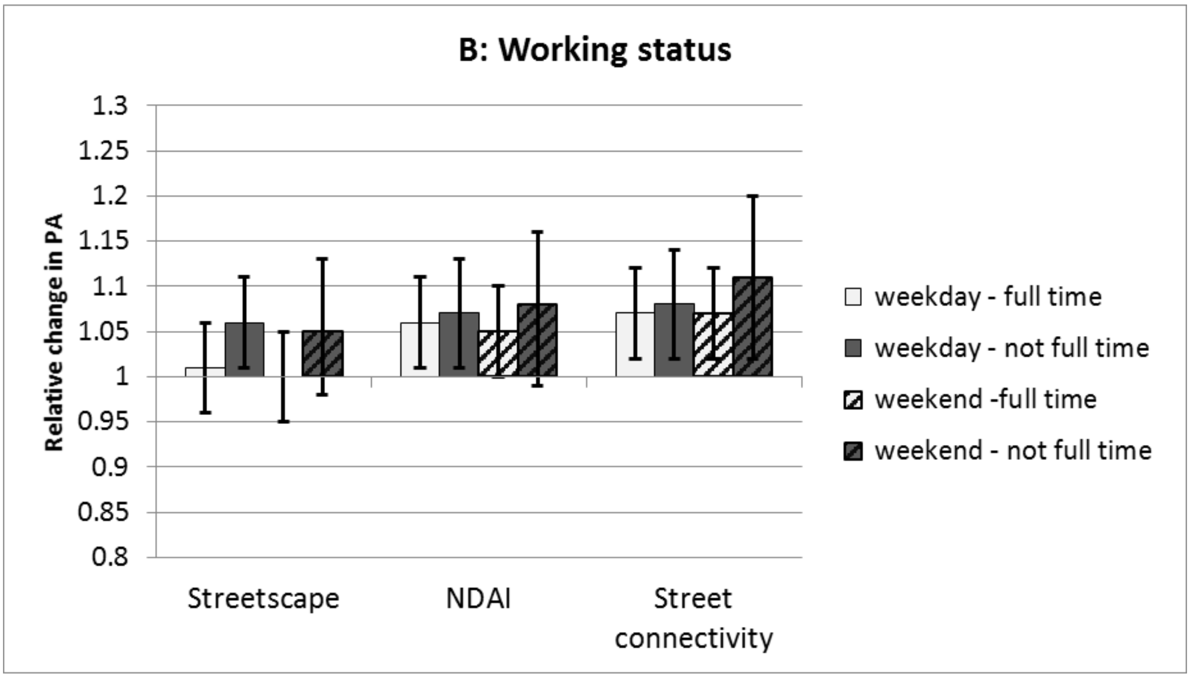
Exposures		***Physical activity: accelerometer average counts per hour (mean (SD))***	
Built Environment		**Weekday**	**Weekend**
Streetscape	*Tertile 1 (least supportive)*	8802 (4411)	8793 (5580)
	Tertile 2	9078 (5214)	8504 (4923)
	Tertile 3 (most supportive)	9681 (5280)	9650 (6406)
Neighbourhood Destinations (NDAI)	*Tertile 1 (least destinations)*	8656 (4687)	8928 (5771)
	Tertile 2	9049 (4749)	8322 (4801)
	Tertile 3 (most destinations)	9944 (5476)	9692 (6295)
Street connectivity	*Tertile 1 (least connected)*	8679 (4492)	8874 (5278)
	Tertile 2	9020 (5076)	8483 (5396)
	Tertile 3 (most connected)	9898 (5315)	9620 (6304)
Covariates			
Gender	*Men*	9532 (5475)	9151 (5924)
	Women	8935 (4594)	8860 (5506)
Age (years)	*15-29*	9043 (4709)	8828 (5553)
	30-34	9240 (4931)	8966 (5566)
	45-54	9165 (5137)	8763 (5651)
	55-65	9192 (5280)	9426 (6068)
Ethnicity	*Māori*	8880 (5171)	7680 (5067)
	Non-Māori	9226 (4268)	9142 (5739)
Education attainment	*No qualification*	9276 (5247)	8385 (5109)
	School	9865 (5712)	9248 (5642)
	Post school	9140 (4688)	8590 (5475)
	Tertiary	8986 (4749)	9561 (6118)
Marital status	*Never married*	9992 (5387)	9192 (6394)
	married	9048 (4824)	9055 (5455)
	Previous married	8542 (4986)	8258 (5547)
NZ index of Deprivation quintiles	*Quintile 1 (Least deprived)*	9200 (4390)	1008 2(6118)
	Quintile 2	9368 (5214)	8947 (5234)
	Quintile 3	9232 (5053)	9306 (5934)
	Quintile 4	8613 (4979)	8489 (5755)
	Quintile 5 (Most deprived)	9600 (5307)	7932 (5044)
Paid working status	*fulltime*	9300 (5030)	9393 (5808)
	not fulltime	9005 (4912)	8364 (5454)
Household Income ($NZ)	*>$60,001*	9149 (4665)	9490 (5734)
	<$60,000	9409 (5512)	8326 (5549)
Car access	*Full access*	9080 (4892)	8924 (5513)
	Restricted or no access	9708 (5430)	9215 (6437)

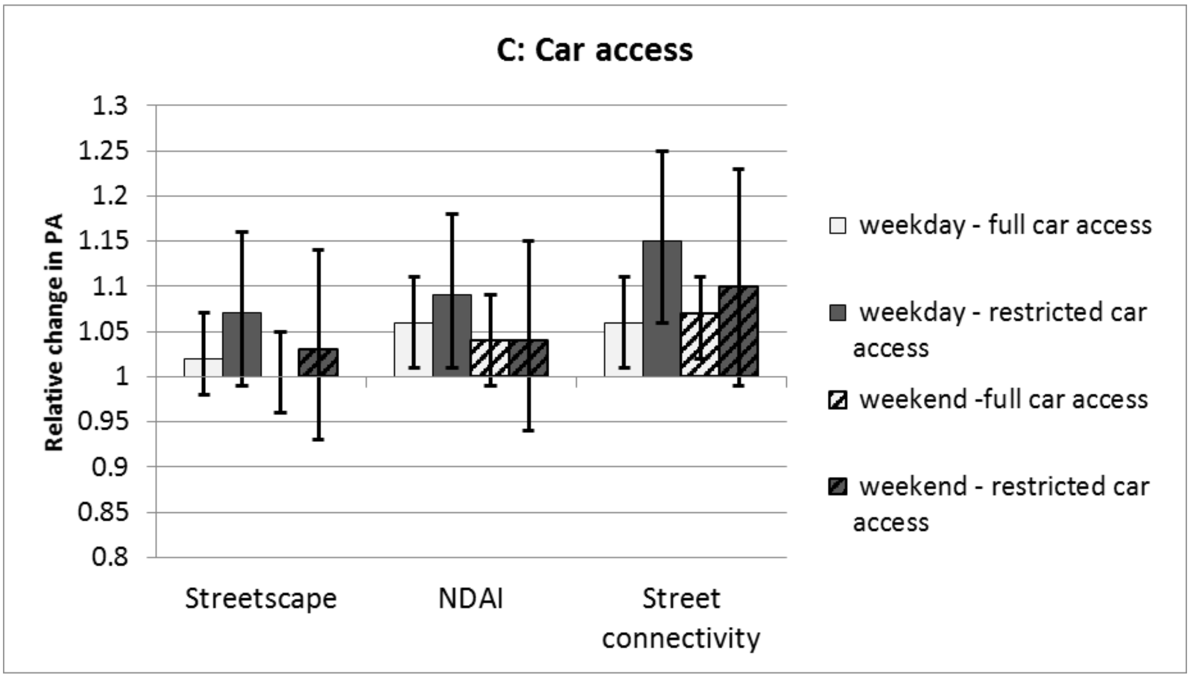
Table 2: Relative change in physical activity for a one standard deviation change in neighbourhood exposure: interaction models

Relative change in accelerometer count per hour (95% CI)	***Streetscape***		***Neighbourhood destinations (NDAI)***		***Street connectivity***	
	Weekday	**weekend**	**Weekday**	**weekend**	**Weekday**	**weekend**
	N=1641	**N=1536**	**N=1641**	**N=1536**	**N=1641**	**N=1536**
Gender interactions						
Built Environment	1.00 (0.95-1.05)	1.00 (0.94-1.06)	1.07 (1.02-1.13)	1.05 (0.99-1.11)	1.08 (1.03-1.13)	1.06 (1.00-1.12)
Women	0.97 (0.92-1.02)	0.99 (0.93-1.06)	0.97 (0.92-1.02)	0.99 (0.93-1.06)	0.97 (0.92-1.02)	0.99 (0.93-1.05)
Built Environment*women	1.06 (1.00-1.11) P=0.042**	1.04 (0.97-1.10) P=0.266	1.00 (0.95-1.06) P=0.910	1.01 (0.95-1.08) P=0.665	0.99 (0.94-1.05) P=0.793	1.03 (0.97-1.10) P=0.378
Working status interactions						
Built Environment	1.01 (0.96-1.05)	1.00 (0.95-1.05)	1.08 (1.03-1.13)	1.05 (0.99-1.10)	1.08 (1.04-1.13)	1.07 (1.01-1.12)
Not working full time	0.98 (0.92-1.03)	0.95 (0.89-1.02)	0.98 (0.92-1.03)	0.95 (0.89-1.02)	0.98 (0.92-1.03)	0.95 (0.89-1.02)
Built Environment* Not working full time	1.06 (1.01-1.12) P=0.022**	1.05 (0.98-1.12) P=0.147	0.99 (0.94-1.05) P=0.737	1.03 (0.96-1.09) P=0.440	0.98 (0.92-1.03) P = 0.354	1.03 (0.97-1.10) P=0.311
Car access interactions						
Built Environment	1.02 (0.98-1.07)	1.01 (0.96-1.06)	1.06 (1.01-1.11)	1.04 (0.99-1.09)	1.06 (1.01-1.10)	1.06 (1.01-1.11)
Restricted car access	1.04 (0.97-1.12)	1.05 (0.96-1.14)	1.03 (0.95-1.11)	1.03 (0.94-1.13)	1.01 (0.94-1.09)	1.01 (0.92-1.11)
Built Environment* Restricted car access	1.06 (0.99-1.13) P=0.108	1.06 (0.98-1.15) P=0.161	1.05 (0.99-1.12) P=0.107	1.06 (0.99-1.14) P=0.112	1.10 (1.02-1.18) P=0.009**	1.11 (1.02-1.21) P=0.013**
Income interactions						
Built Environment	1.01(0.96-1.06)	1.01 (0.96-1.07)	1.05 (1.00-1.10)	1.05 (0.99-1.11)	1.05 (1.01-1.10)	1.06 (1.01-1.12)
Low income	0.99 (0.93-1.05)	0.89 (0.83-0.96)	0.99 (0.93-1.06)	0.90 (0.83-0.97)	0.99 (0.93-1.05)	0.90 (0.83-0.96)
Built Environment* low income	1.06 (1.00-1.12) P=0.035 **	1.02 (0.95-1.09) P=0.559	1.05 (0.99-1.11) P=0.081*	1.02 (0.95-1.09) P=0.598	1.07 (1.01-1.13) P=0.028**	1.05 (0.98-1.13) P=0.180

[1] fully adjusted model including confounders (age, marital status, education attainment, ethnicity, neighbourhood deprivation) and the potential effect modifiers (sex, working status, car access, household income), and with interaction term added.
NDAI, Neighbourhood Destination Access Index
* $p<0.10$
** $p<0.05$


A: Gender
Relative change in PA
1.3
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
Streetscape
NDAI
Street connectivity
weekday - men
weekday -women
weekend -men
weekend - women


B: Working status
Relative change in PA
1.3
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
Streetscape
NDAI
Street connectivity
weekday - full time
weekday - not full time
weekend -full time
weekend - not full time



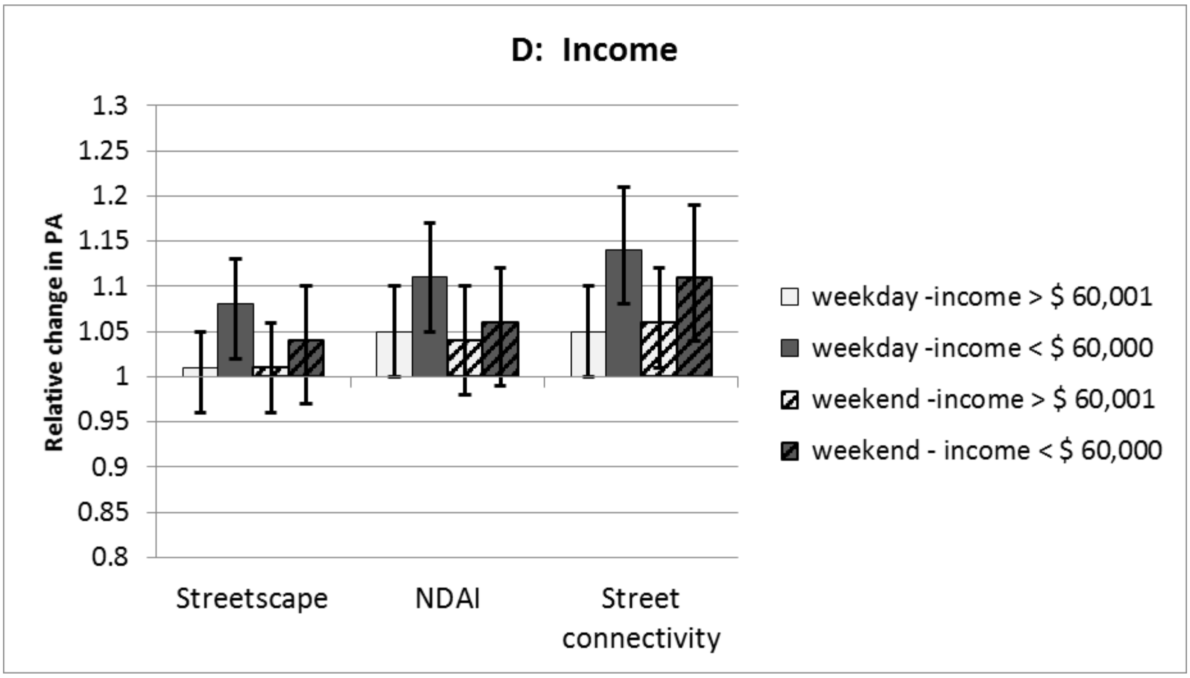
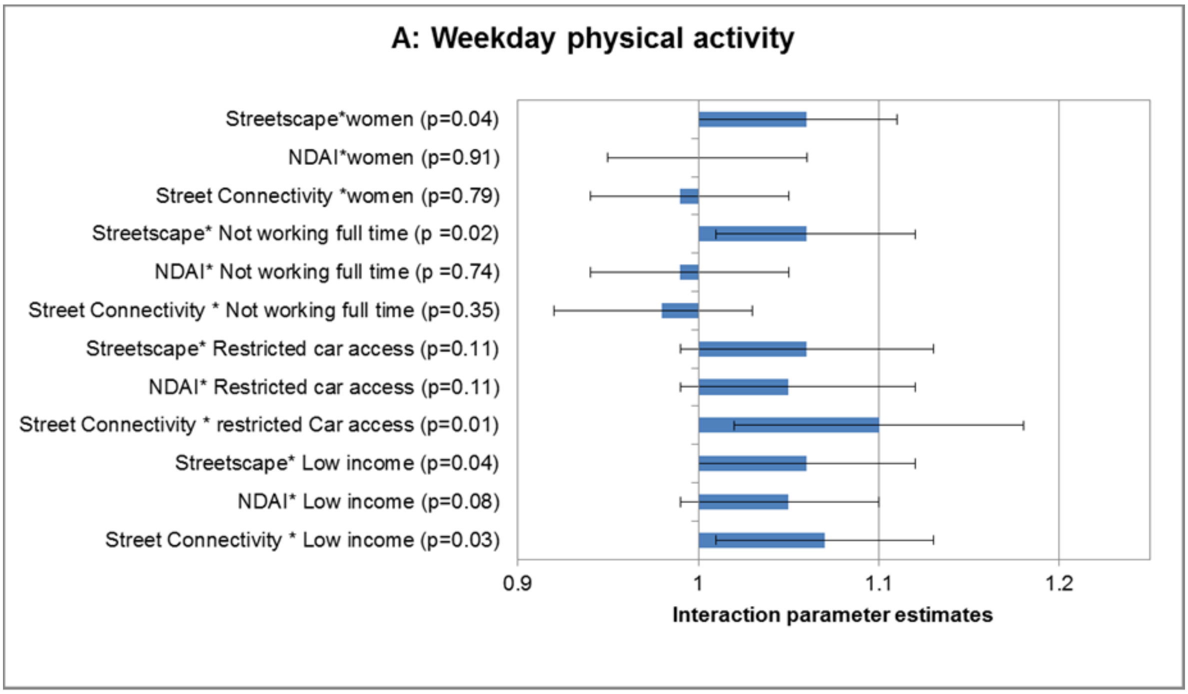
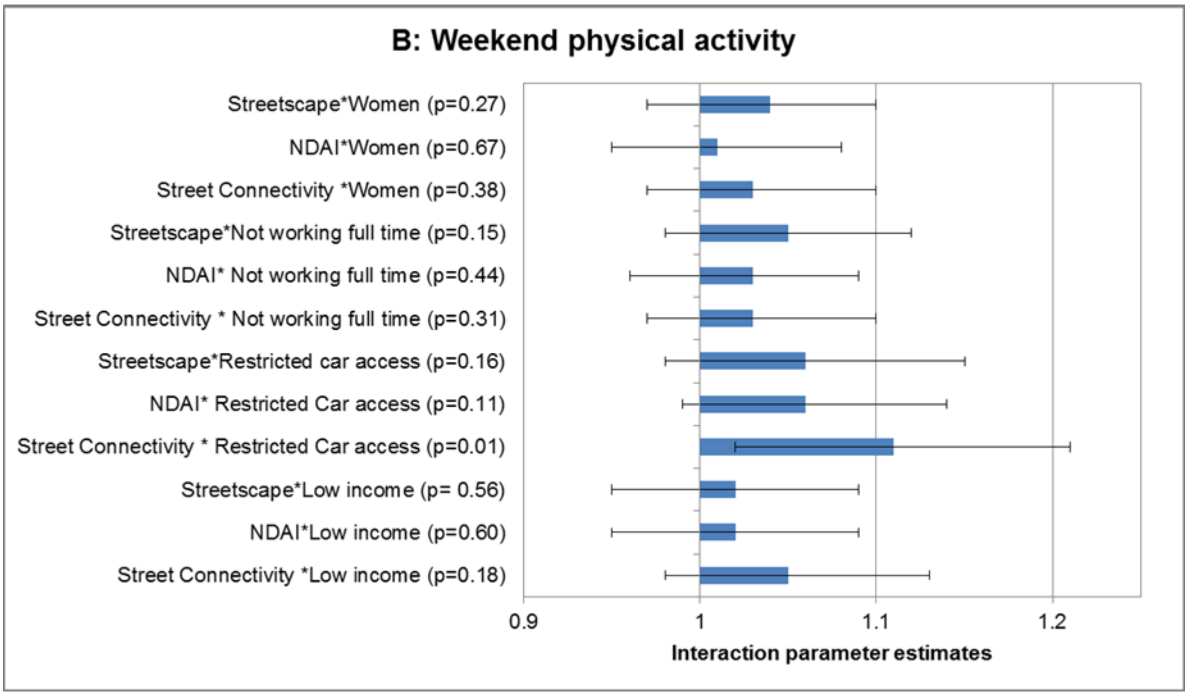


Figure 1:a-d: Built environment and physical activity stratified by potential effect modifiers


A: Weekday physical activity
Streetscape*women (p=0.04)
NDAI*women (p=0.91)
Street Connectivity *women (p=0.79)
Streetscape* Not working full time (p =0.02)
NDAI* Not working full time (p =0.74)
Street Connectivity * Not working full time (p=0.35)
Streetscape* Restricted car access (p=0.11)
NDAI* Restricted car access (p=0.11)
Street Connectivity * restricted Car access (p=0.01)
Streetscape* Low income (p=0.04)
NDAI* Low income (p=0.08)
Street Connectivity * Low income (p=0.03)
0.9
1
1.1
1.2
Interaction parameter estimates


B: Weekend physical activity
Streetscape*Women (p=0.27)
NDAI*Women (p=0.67)
Street Connectivity *Women (p=0.38)
Streetscape*Not working full time (p=0.15)
NDAI* Not working full time (p=0.44)
Street Connectivity * Not working full time (p=0.31)
Streetscape*Restricted car access (p=0.16)
NDAI* Restricted Car access (p=0.11)
Street Connectivity * Restricted Car access (p=0.01)
Streetscape*Low income (p= 0.56)
NDAI*Low income (p=0.60)
Street Connectivity *Low income (p=0.18)
0.9
1
1.1
1.2
Interaction parameter estimates