

# BMJ Open

## Developing and testing theory: Understanding the role of perceptions of environmental infrastructure intervention to promote physical activity in a natural experiment study

Journal:	<i>BMJ Open</i>
Manuscript ID:	bmjopen-2015-007593
Article Type:	Research
Date Submitted by the Author:	06-Jan-2015
Complete List of Authors:	Panter, Jenna; University of Cambridge, UKCRC Centre for Diet and Activity Research (CEDAR) Ogilvie, David; University of Cambridge, UKCRC Centre for Diet and Activity Research (CEDAR)
<b>Primary Subject Heading</b>:	Public health
Secondary Subject Heading:	Epidemiology
Keywords:	EPIDEMIOLOGY, PREVENTIVE MEDICINE, PUBLIC HEALTH

SCHOLARONE™  
Manuscripts

1  
2 1 **Title: Developing and testing theory: Understanding the role of perceptions of environmental**  
3  
4 2 **infrastructure intervention to promote physical activity in a natural experiment study**  
5  
6  
7 3

8 4 **Authors:** Jenna Panter and David Ogilvie on behalf of the iConnect consortium  
9

10 5 **Affiliation:** Medical Research Council Epidemiology Unit and UKCRC Centre for Diet and  
11  
12 6 Activity Research (CEDAR), University of Cambridge, Box 285, Cambridge Biomedical Campus,  
13  
14 7 Cambridge, CB2 0QQ, UK.  
15

16  
17 8 **Corresponding author information:** Jenna Panter, Medical Research Council Epidemiology Unit  
18  
19 9 and UKCRC Centre for Diet and Activity Research (CEDAR), University of Cambridge, Box 285,  
20  
21 10 Cambridge Biomedical Campus, Cambridge, CB2 0QQ, UK.  
22

23  
24 11 Phone: +44 (0)1223 746884. Fax: +44 (0)1223 330316. Email: [jenna.panter@mrc-epid.cam.ac.uk](mailto:jenna.panter@mrc-epid.cam.ac.uk)  
25  
26  
27 12  
28  
29 13  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

14  
15 **ABSTRACT:**

16 **Objective:** Some studies have assessed the effectiveness of environmental interventions to  
17 promote physical activity, but few have examined how such interventions work. We investigated  
18 the environmental mechanisms linking the intervention with behaviour change.

19 **Design:** Natural experimental study

20 **Setting:** Three UK municipalities (Southampton, Cardiff and Kenilworth)

21 **Participants:** Adults living within 5km of new walking and cycling infrastructure

22 **Intervention:** Construction or improvement of walking and cycling routes. Exposure to the  
23 intervention was defined in terms of residential proximity.

24 **Outcome measures:** Questionnaires at baseline and two-year follow-up assessed perceptions of  
25 the supportiveness of the environment, use of the new infrastructure, and walking and cycling  
26 behaviours. Analysis proceeded via factor analysis of perceptions of the physical environment  
27 (step 1) and regression analysis to identify plausible pathways involving physical and social  
28 environmental mediators and refine the intervention theory (step 2) to a final path analysis to test  
29 the model (step 3).

30 **Results:** Participants who lived near and used the new routes reported increases in their  
31 perceptions of infrastructure provision and safety. However, path analysis (step 3, n=967) showed  
32 that the effects of the intervention on changes in time spent walking and cycling were largely  
33 (90%) explained by a simple causal pathway involving use of the new routes, and other pathways  
34 involving changes in environmental cognitions explained only a small proportion of the effect.

35 **Conclusions:** Physical improvement of the environment itself was the key to the effectiveness of  
36 the intervention, and seeking to change people's perceptions may be of limited value. Studies of  
37 how interventions lead to population behaviour change should complement those concerned with  
38 estimating their effects in supporting valid causal inference.

39

40 **Key words:** causality, environment design, evaluation, health promotion

## 41 Article Summary

- 42 • In the context of an intervention to change environmental determinants of health, we  
43 systematically identified the environmental mediators of changes in walking and cycling in  
44 a population-based sample.
- 45 • Such evidence for *how* an intervention achieves its effects (*causal explanation*) can be  
46 combined with the evidence for the size of those effects (*causal estimation*) reported  
47 elsewhere to provide a stronger basis for valid causal inference.
- 48 • We cannot be certain if changes in mediators led to changes in physical activity or vice  
49 versa as these were assessed over the same time period. However, most existing research  
50 on the mediators of the relationship between physical activity and the environment has  
51 explored cross-sectional associations, our analysis used longitudinal data from an  
52 intervention study in which environmental changes were known to have been introduced.
- 53 • We restricted our analysis to participants with complete data on all mediators, which  
54 produced a sample for analysis that was somewhat younger and healthier than the main  
55 study sample.
- 56 • Stronger evidence of mediation may have been found for other unmeasured environmental  
57 attributes more closely related to recreational activities or other psychological constructs  
58 such as confidence, intention or self-efficacy, which were not the focus of this study.

## 61 INTRODUCTION

### 63 Physical activity and the environment

64 Promoting physical activity is a public health priority,<sup>1</sup> and walking and cycling are potential  
65 targets for intervention strategies because they are relatively easy to integrate into daily life and  
66 may confer substantial individual health benefits<sup>2</sup> and wider social and environmental co-benefits<sup>3</sup>

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

67 <sup>4</sup>. However, efforts to encourage walking and cycling at the population level have met with modest  
68 success to date.<sup>5-7</sup> It is argued that changing the environment may be required to produce broader  
69 and more sustained effects, but this is mostly based on evidence from cross-sectional observational  
70 studies. These suggest that factors such as distance to destinations, density and land use mix may  
71 be important influences on walking and cycling,<sup>8 9</sup> but there are few longitudinal studies  
72 examining the environmental determinants of behaviour change or evaluating the impact of  
73 environmental changes.<sup>5-11</sup> While these latter types of study are gradually shifting the focus of  
74 research from correlation towards causation, they sometimes report null associations for  
75 environmental attributes found to be significant in cross-sectional studies.<sup>11</sup> Even where well  
76 designed studies have provided a relatively unbiased estimate of the effect size for an  
77 environmental intervention (*causal estimation*), some authors argue that valid causal inference in  
78 public health also depends on showing *how* an intervention brings about the outcomes attributed to  
79 it (*causal explanation*).<sup>12 13</sup>

### 81 **In search of causal explanation for environmental interventions**

82 A variety of social and physical environmental factors, such as those depicted in socio-ecological  
83 models of health,<sup>14</sup> are widely acknowledged to be important influences on physical activity  
84 behaviour. However these models generally provide a broad framework indicating the existence of  
85 such influences at multiple levels, rather than considering *specifically* how behaviour is postulated  
86 to change in response to environmental changes. Understanding such mechanisms could be  
87 expected to clarify the significance and role of specific factors along the putative casual pathway  
88 linking environmental change to physical activity behaviour change,<sup>12 13 15</sup> but few studies have  
89 attempted to do this.<sup>11</sup> This may reflect the fact that the casual pathways for public health  
90 interventions can be long and complex.<sup>13</sup> Nevertheless, investigating how changes to the  
91 environment are perceived and acted upon could provide greater understanding of how  
92 interventions work and thereby inform the design and targeting of future interventions.<sup>13 15</sup>

1  
2 933  
4 94 **The iConnect study**5  
6 95 Connect2 is a programme of projects to promote walking and cycling at 79 sites around the UK.7  
8 96 Each comprises a core engineering project such as a bridge over a busy road, railway or river,9  
10 97 which together with the development or improvement of feeder routes was intended to make it11  
12 98 easier for pedestrians and cyclists to reach destinations in their local area13  
14 99 ([www.lotterygoodcauses.org.uk/project/sustrans-connect2](http://www.lotterygoodcauses.org.uk/project/sustrans-connect2)). The iConnect study began with the15  
16 100 development of a general theoretical framework and a preliminary intervention model that was17  
18 101 used to guide data collection and analysis.<sup>16</sup> Briefly, the model postulated that a Connect2 project19  
20 102 may alter the physical accessibility of local destinations and other potentially relevant21  
22 103 characteristics of the environment, such as the convenience and safety of routes for walking or23  
24 104 cycling. It was always intended that this preliminary intervention model would be tested and25  
26 105 refined in longitudinal analysis.<sup>16</sup> The main outcome evaluation has shown positive effects of the27  
28 106 intervention on walking, cycling and overall physical activity after two years,<sup>17</sup> and qualitative29  
30 107 interviews have highlighted the potential importance of visibility of the new infrastructure in31  
32 108 fostering behaviour change in local people.<sup>18</sup> In this paper, we build on these findings by33  
34 109 investigating the ‘environmental’ mechanisms linking the intervention with behaviour change. We35  
36 110 did not set out to test all the potential causal mechanisms for behaviour change in this context,37  
38 111 such as those involving psychological constructs such as confidence, intention or self-efficacy.39  
40 112 Instead we have focused on that part of the causal pathway most proximally related to the41  
42 113 intervention, which relates to perceptions of changes in the environment and use of the new43  
44 114 infrastructure. We systematically describe and test a series of hypothesised mediating processes,45  
46 115 seeking to identify not only which mediators are important but also their most plausible causal47  
48 116 ordering. We then use the findings to refine the overall intervention model and subsequently to49  
50 117 assess the relative contributions of the different pathways to behaviour change.51  
52 118

1  
2 119 **METHODS**  
3  
4

5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

121 **Intervention, settings and data collection procedures**

122 A more detailed description of the intervention, settings and data collection procedures is available  
123 elsewhere.<sup>19</sup> Briefly, three Connect2 projects in Cardiff, Kenilworth (Warwickshire) and  
124 Southampton were purposively selected as case study sites according to criteria including  
125 implementation timetable, likelihood of measurable population impact, and heterogeneity of  
126 overall mix of sites.<sup>16 19</sup> In Cardiff, pedestrians and cyclists travelling between the city centre and  
127 the suburbs across Cardiff Bay had to share space with motor vehicles on a busy road, and the  
128 centrepiece of the Connect2 project was a new 140m long, 4m wide traffic-free bridge with  
129 integral lighting. In Kenilworth a new traffic-free bridge was built across a busy trunk road to link  
130 the town to a rural greenway, and in Southampton a new 400m boardwalk was built along the  
131 shore of the tidal River Itchen, replacing an informal footpath which was impassable at high tide.  
132 Each project included improvements to feeder routes which linked the new infrastructure with  
133 existing route networks.

134

135 Questionnaires were posted to 22,500 adults who were listed on the edited electoral register as  
136 living within 5km by road of the core Connect2 project at any of the three sites in April 2010.  
137 3516 individuals returned questionnaires at baseline and were followed up in April 2012 after the  
138 opening of the new infrastructure. Information on demographic and socio-economic  
139 characteristics, travel and physical activity behaviours, and perceptions of the environment were  
140 collected at both time points and additional questions were asked at follow-up to assess use of the  
141 Connect2 project. The questionnaire is published in full elsewhere <sup>19</sup>. The University of  
142 Southampton Research Ethics Committee granted ethical approval (CEE200809-15) and all  
143 participants provided written informed consent.

144

1  
2 145 **Measures**  
3

4 146 As the main outcome evaluation showed that residential proximity to the new routes predicted  
5  
6 147 increases in weekly time spent walking and cycling (the primary outcome) <sup>17</sup>, we used the same  
7  
8 148 measures of intervention exposure and outcome in this analysis.  
9

10  
11 149

12  
13 150 *Exposure*  
14

15 151 Those living closer to the Connect2 projects were deemed to be more highly exposed to the  
16  
17 152 intervention than those living further away. Proximity to Connect2 was assessed using the shortest  
18  
19 153 distance between each participant's home address and the nearest access point to the 'greater  
20  
21 154 Connect2' project (including feeder routes) using an enhanced road network which included traffic  
22  
23 155 free and informal paths <sup>19</sup>.  
24  
25

26 156

27  
28 157 *Outcome*  
29

30 158 Walking and cycling for transport were assessed using a seven-day recall instrument covering  
31  
32 159 journeys made for five purposes: for commuting, on business, for study, for shopping and personal  
33  
34 160 business, and for social activities <sup>19</sup>. Participants reported the total time spent travelling for each  
35  
36 161 purpose by each of seven modes of transport including 'walking' and 'cycling', and these were  
37  
38 162 summed across all purposes for each mode of travel. Recreational physical activity was measured  
39  
40 163 using an adapted version of the short form of the International Physical Activity Questionnaire in  
41  
42 164 which participants reported the total time spent walking for recreation and cycling for recreation in  
43  
44 165 the past week <sup>20</sup>. Total weekly time spent walking and cycling was derived by summing the times  
45  
46 166 spent walking and cycling for transport and for recreation, and change scores were computed as  
47  
48 167 the time reported at follow-up minus the time reported at baseline.  
49

50  
51 168

52  
53 169 *Mediators*  
54  
55  
56  
57  
58  
59  
60



1  
2 170 We hypothesised that the effects of Connect2 on overall walking and cycling may come about as a  
3  
4 171 result of participants' awareness of improvements in the physical and social environmental  
5  
6 172 conditions for those behaviours and their use of the new routes, which we investigated as potential  
7  
8 173 mediators. At both time points, participants were asked to report their agreement with seven items  
9  
10 174 referring specifically to the physical environment traversed by the Connect2 project using a five-  
11  
12 175 point Likert scale from strongly disagree (-2) to strongly agree (+2) (Table 1). Four additional  
13  
14 176 items asked about the visibility of walking for travel, walking for recreation, cycling for travel and  
15  
16 177 cycling for recreation 'in my neighbourhood'. Change scores for each of the physical  
17  
18 178 environmental items were computed as the difference between the baseline and follow-up  
19  
20 179 measures, while change in the visibility of walking and cycling was summarised using the mean of  
21  
22 180 the corresponding change scores for the four individual items. At follow-up, participants were also  
23  
24 181 asked if they had walked or cycled on the Connect2 project (yes/no).  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

182

183

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49

184 **Table 1:** Items assessing (changes in) the perceived physical and social environment and rotated factor loadings

185

Description	Item	Factor 1 'Change in infrastructure',	Factor 2 'Change in safety'
<b>Perceived physical environment</b>			
Safety for walking	Walking is unsafe because of the traffic	0.276	<b>0.809</b>
Safety for cycling	Cycling is unsafe because of the traffic	0.243	<b>0.804</b>
Pavements for walking	There are pavements suitable for walking	<b>0.732</b>	0.221
Special lanes for cycling	There are special lanes, routes or paths for cycling	<b>0.688</b>	0.280
Pleasant	The routes are pleasant for walking or cycling	<b>0.706</b>	0.203
Low crime	The level of crime or anti-social behaviour means walking or cycling is	-0.128	<b>0.678</b>
Lighting	The routes for walking and cycling are generally well lit at night	<b>0.695</b>	0.032
<b>Perceived social environment</b>			
Perceived visibility of cycling for	I see people in my neighbourhood cycling for travel	n/a	n/a
Perceived visibility of walking for	I see people in my neighbourhood walking for travel	n/a	n/a
Perceived visibility of cycling for	I see people in my neighbourhood cycling for recreation	n/a	n/a
Perceived visibility of walking for	I see people in my neighbourhood walking for recreation	n/a	n/a

186  
187  
188  
189

n/a: not applicable as this variable was not used in factor analysis. Factor analysis was based on 1211 participants for whom change scores for all relevant items were available.

### *Covariates*

All demographic (sex, age, ethnicity and presence of any child under 16 in the household), socioeconomic (highest educational level, annual household income and employment status) and health variables (height, weight, general health, and presence of long-term illness or disability limiting daily activities) were self-reported at baseline by participants. Height and weight were used to compute body mass index and assign participants to one of three categories of weight status based on internationally recognised cut-offs <sup>21</sup>.

### **Analysis**

Our analysis was divided into three steps. We first explored the factor structure of the items assessing perceptions of the physical environment, to identify whether groups of items were related and changed in similar ways (step 1: see below). This reflected the fact that the Connect2 projects aimed to improve the environment for walking and cycling more generally, rather than targeting single aspects such as safety or pleasantness. We then identified candidate mediators and their most plausible conceptual ordering by systematically exploring the associations between the environmental perception measures (factor scores for the physical environmental items, and the mean change score for the visibility items), proximity to and use of Connect2, and change in time spent walking and cycling (step 2). Having thereby refined our intervention theory, we then used path analysis — a confirmatory analysis technique — to formally test the model and estimate the magnitude and significance of the hypothesised causal relationships between the sets of variables <sup>22</sup> (step 3). All analyses were restricted to participants who had not moved home during the study and whose total reported physical activity had not changed by >900 min/week, which may have come about as a result of misreporting (e.g. misreporting 15 minutes as 15 hours). Steps 1 and 2 were conducted using STATA, and step 3 using Mplus.

#### *Step 1: Factor analysis of changes in perceptions of the physical environment*

1  
2 A principal components analysis was conducted on the items assessing perceptions of the physical  
3 environment at baseline and at follow-up, as well as on the change scores. Factors with an  
4 eigenvalue less than one were dropped, factor loadings were rotated using varimax (orthogonal)  
5 rotation and factors were scored by the method suggested by Bartlett<sup>23</sup>, creating scores for each  
6 factor weighted according to the item loadings<sup>24</sup>. These analyses were further restricted to  
7 participants who had completed all the physical environmental perception items at both time  
8 points.  
9  
10  
11  
12  
13  
14  
15  
16

### 17 18 19 20 *Step 2: Identification of mediators and refinement of intervention theory*

21 We systematically tested the associations (i) between proximity to Connect2 and the hypothesised  
22 mediators (changes in the environmental perception measures and use of Connect2); (ii) between  
23 these hypothesised mediators and change in walking and cycling; and (iii) between the various  
24 mediators. We fitted separate linear or logistic regression models as appropriate for all the  
25 associations tested. These were adjusted for time spent walking and cycling at baseline and all the  
26 demographic, socioeconomic and health characteristics listed above, but were not adjusted for the  
27 other mediators. The objective was not to isolate statistically significant single associations, but to  
28 identify plausible links in a causal pathway to be carried forward to the next stage of analysis, as  
29 advocated by Victora and colleagues<sup>13</sup>. We therefore applied a generous criterion of  $p < 0.25$  to  
30 identify 'plausible' associations at this stage. However, because the aim of the analysis was to  
31 elucidate mechanisms for an *intervention* that had already been shown to be positively associated  
32 with the behaviour change outcomes, we carried forward only those mediators that were directly  
33 associated with both the exposure and either the outcome or another mediator, and for which all  
34 the observed associations were in the expected (i.e. positive) direction.  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54

### 55 *Step 3: Testing the intervention model*

56  
57  
58  
59  
60

1  
2 The resulting model was tested using path analysis, in other words using a structural equation  
3 model with no latent variables. This approach allows sets of relationships between variables to be  
4 modelled simultaneously, using linear or logistic regression as appropriate according to the form  
5 of the dependent variables and with the mediating variables being treated as both dependent and  
6 independent variables<sup>25</sup>. It is a confirmatory form of analysis in which a model depicting  
7 unidirectional causal effects of one variable on another is tested with no possibility of  
8 incorporating feedback loops<sup>26</sup>. We adopted a complete case approach, restricting these analyses  
9 to participants who had provided data on exposure, outcome and all mediators and covariates, and  
10 used maximum likelihood estimation with 1000 iterations.  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23

### 24 *Stratified analyses*

25  
26 We further hypothesised that different mechanisms of behaviour change may operate in people  
27 with different levels of walking and cycling prior to the intervention. We therefore divided the  
28 sample at the median total time spent walking and cycling at baseline (190 min/week) and repeated  
29 steps 2 and 3 in the low-active and high-active subgroups. Because there remained significant  
30 variation in baseline activity within each subgroup, we also adjusted for time spent walking and  
31 cycling at baseline in these models.  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41

## 42 **RESULTS**

### 43 **Sample characteristics**

44  
45  
46  
47 1510 participants returned survey data at baseline and follow-up, of whom 1465 met the inclusion  
48 criteria for the main outcome evaluation and 1211 provided information sufficient for the factor  
49 analysis in step 1. The sample size for each regression model in step 2 ranged from 969 to 1139  
50 according to the completeness of reporting of the various mediators. 967 participants provided  
51 complete data on exposure, outcome, and all mediators and covariates, and comprised the sample  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2 for the analysis in step 3. Compared to the sample of 1465 used for the main outcome evaluation  
3  
4 <sup>17</sup>, our final subsample was slightly younger on average and included a higher proportion of men  
5  
6 (Table 2). Participants in this final subsample were also more likely to be educated to tertiary  
7  
8 level, to have access to a car and to a bicycle and to have a child in their household, and less likely  
9  
10 to report having a long term health condition (all  $p < 0.001$ ). However, our subsample was not  
11  
12 significantly different from the main sample in terms of ethnicity, weight status or time spent  
13  
14 walking and cycling at baseline.  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

**Table 2:** Characteristics of the sample

Variable	Category	Participants providing data on exposure and outcome (n=1465) % (N)	Participants providing data on exposure, outcome and all mediators and covariates (n=967) % (N)
Site	Cardiff	32.3 (473)	33.6 (325)
	Kenilworth	39.9 (584)	40.7 (394)
	Southampton	27.9 (408)	25.7 (248)
Residential proximity to intervention (km)	≥4	9.6 (141)	9.7 (93)
	3-3.99	7.0 (103)	6.9 (66)
	2-2.99	15.2 (222)	15.2 (147)
	1-1.99	32.4 (474)	31.6 (306)
	<1	35.8 (525)	36.6 (355)
Sex	Female	56.7 (831)	51.9 (502)
	Male	43.3 (634)	48.1 (465)
Age (years) at baseline	18-34	9.7 (141)	11.0 (107)
	35-49	19.9 (291)	24.1 (233)
	50-64	35.5 (519)	38.5 (372)
	65-89	34.9 (510)	26.4 (255)
Ethnicity	White	96.9 (1417)	97.2 (940)
	Non-White	3.1 (45)	2.8 (27)
Any child under 16 in household	No	84.4 (1236)	81.1 (784)
	Yes	15.6 (229)	18.9 (183)
Highest educational level	Tertiary or higher	39.5 (576)	45.9 (444)
	Secondary school	32.8 (479)	32.9 (318)
	Lower than secondary	27.7 (405)	21.2 (205)
Annual household Income	>£40,000	32.1 (439)	36.6 (355)
	£20,001-40,000	33.7 (461)	35.0 (339)
	≤£20,000	34.3 (469)	28.4 (275)
Employment Status	Working	49.2 (720)	56.7 (548)
	Student	1.6 (24)	1.4 (14)
	Retired	40.3 (589)	33.2 (321)
	Other	8.9 (130)	8.7 (84)
Any car in household	No	13.9 (203)	10.0 (97)
	Yes	86.1 (125)	90.0 (872)
Any adult bicycle in household	No	44.6 (603)	39.5 (382)
	Yes	55.4 (748)	60.5 (585)
Weight status	Normal/underweight	49.0 (683)	48.4 (469)
	Overweight	37.0 (515)	37.6 (364)
	Obese	14.0 (195)	14.0 (136)
General health	Excellent/good	78.5 (113)	81.6 (789)
	Fair/poor	21.5 (312)	18.4 (178)
Long-term illness or disability that limits daily activities	No	74.0 (102)	78.1 (757)
	Yes	26.0 (359)	21.9 (212)
Time spent walking and	None	15.6 (229)	14.0 (136)

Variable	Category	Participants providing data on exposure and outcome (n=1465)  % (N)	Participants providing data on exposure, outcome and all mediators and covariates (n=967)  % (N)
cycling in past week (min)	1-149	25.7 (376)	27.2 (264)
	150-299	23.5 (344)	23.6 (229)
	300-449	14.4 (211)	14.2 (138)
	≥450	20.8 (305)	20.9 (202)

For peer review only



### Step 1: Factor analysis of changes in perceptions of the physical environment

The results of the factor analyses of the baseline and follow-up values were similar to those of the factor analysis of the change scores (Additional File 1). We therefore chose to use the factors and factor scores derived from the change scores. We identified two meaningful factors, which we described as representing perceived changes in infrastructure (eigenvalue: 2.9) and perceived changes in safety (eigenvalue: 1.2) (Table 1). These factors explained 58% of the variance in the change scores for the physical environmental perception items.

### Step 2: Identification of mediators and refinement of intervention theory

#### *Whole sample*

Table 3 summarises the associations between the putative mediators, proximity to Connect2 and change in time spent walking and cycling. As reported elsewhere<sup>17 27</sup>, proximity to Connect2 was associated with use (OR=1.85,  $p<0.001$ ; Table 3a) and use of Connect2 was associated with change in time spent walking and cycling ( $\beta=31.16$ ,  $p=0.06$ ; Table 3b). Proximity to Connect2 was associated with perceived changes in infrastructure and visibility (both  $\beta=0.05$ ,  $p\leq 0.03$ ) and safety ( $\beta=0.03$ ,  $p=0.18$ ; Table 3c). Although all of these also met the criteria for a plausible association with use of Connect2 ( $1.23\leq OR\leq 1.33$ , all  $p\leq 0.008$ ; Table 3d), only a perceived change in safety was directly associated with change in time spent walking and cycling ( $\beta=9.19$ ,  $p=0.22$ ; Table 3e). The association between perceived changes in infrastructure and visibility also met the criteria for inclusion ( $\beta=0.06$ ,  $p=0.04$ ), while those between perceived changes in safety and infrastructure or visibility did not (Table 3f).

**Table 3:** Associations between potential mediators, proximity to intervention and change in walking and cycling

<b>(a) Associations between proximity to and use of intervention</b>		
<b>Independent variable: Residential proximity to intervention (km)</b>		
<b>Dependent variable</b>	<b>OR (95% CI)</b>	<b>p</b>
Use of intervention (yes/no)	1.85 (1.61, 2.11)	0.001
<b>(b) Associations between use of intervention and change in walking and cycling</b>		
<b>Independent variable: Use of intervention (yes/no)</b>		
<b>Dependent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in time spent walking and cycling (min/week)	31.16 (-1.72, 64.05)	0.063
<b>(c) Associations between proximity to intervention and perceived environmental changes</b>		
<b>Independent variable: Residential proximity to intervention (km)</b>		
<b>Dependent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	0.05 (0.01, 0.10)	0.030
Change in safety	0.03 (-0.02, 0.08)	0.182
Change in visibility	0.05 (0.01, 0.10)	0.013
<b>(d) Associations between perceived environmental changes and use of intervention</b>		
<b>Dependent variable: Use of intervention (yes/no)</b>		
<b>Independent variable</b>	<b>OR (95% CI)</b>	<b>p</b>
Change in infrastructure	1.23 (1.06, 1.44)	0.008
Change in safety	1.31 (1.13, 1.54)	0.001
Change in visibility	1.33 (1.15, 1.55)	0.001
<b>(e) Associations between perceived environmental changes and change in walking and cycling</b>		
<b>Dependent variable: Change in time spent walking and cycling (min/week)</b>		
<b>Independent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	-2.51 (-17.16, 12.13)	0.736
Change in safety	9.19 (-5.36, 23.74)	0.215
Change in visibility	-6.21 (-20.62, 8.19)	0.398
<b>(f) Associations between perceived environmental changes</b>		
<b>Dependent variable: Change in visibility</b>		
<b>Independent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	0.06 (0.00, 0.12)	0.039
Change in safety	0.03 (-0.03, 0.09)	0.328
<b>Dependent variable: Change in safety</b>		
<b>Independent variable</b>		
Change in infrastructure	-0.03 (-0.10, 0.03)	0.215

Linear or logistic regression models as appropriate adjusted for time spent walking and cycling at baseline and the demographic, socioeconomic and health characteristics shown in Table 2. Proximity was modelled as the negative of the distance between home and the nearest access point to the 'greater Connect2 project' including feeder routes. Each row represents a separate model which was not adjusted for the other mediators.

1  
2 Based on these results, a path model was developed to capture the most plausible theory of change  
3 linking proximity to the intervention with change in time spent walking and cycling (Figure 1a).  
4 Perceived changes in infrastructure, safety and visibility were all associated with proximity, and  
5 because these were hypothesised to change as a direct and proximate result of the intervention they  
6 were placed directly after proximity in the model. All three perceived changes were also associated  
7 with use of the intervention, and we assumed that the more plausible causal ordering was that the  
8 changes in the perceived supportiveness of the environment may have led to use of the new  
9 infrastructure. Use was also associated with proximity and with change in time spent walking and  
10 cycling, so we included an additional indirect path between exposure and outcome via use only.  
11 Only one of the interrelationships between the perceived environmental changes – that between  
12 infrastructure and visibility – was identified as plausible, and we assumed that perceived  
13 improvements in infrastructure were more likely to reflect a direct and proximate effect of the  
14 *physical* intervention and may therefore have preceded the perceived change in the visibility of  
15 walking and cycling. Given the lack of clear theory or evidence in relation to the causal ordering  
16 of some of these mediators, however, we developed two alternative models that were also  
17 consistent with the associations observed in step 2: one in which the perceived change in visibility  
18 preceded the perceived change in infrastructure (Alternative 1), and one in which the perceived  
19 change in safety followed use of the infrastructure (Alternative 2; Additional File 2).

#### 20 21 22 *Low-active subgroup*

23 In the low-active subgroup, proximity to Connect2 was associated with use (OR=2.05, p=0.001)  
24 and use of the infrastructure was associated with change in time spent walking and cycling  
25 ( $\beta=62.96$ , p<0.001; Additional File 3a, 3b). Proximity was associated with perceived changes in  
26 safety ( $\beta=0.08$ , p=0.03) and infrastructure ( $\beta=0.05$ , p=0.15), but the association with change in  
27 visibility did not meet the criteria for inclusion (Additional File 3c). Perceived changes in safety  
28 and visibility, but not in infrastructure, met the criteria for a plausible association with use of

1  
2 Connect2 ( $1.14 \leq OR \leq 1.42$ ,  $p < 0.25$ ; Additional File 3d). None of the associations between the  
3  
4 putative mediators and change in time spent walking and cycling met the criteria for inclusion, nor  
5  
6 did those between the various perceived environmental changes (Additional File 3e, 3f). While  
7  
8 perceived changes in infrastructure and visibility therefore met the criteria for inclusion in the  
9  
10 model based on single associations (with proximity and use respectively), they could not be linked  
11  
12 on a pathway and were therefore deemed not to be plausibly causally related to the effects of the  
13  
14 intervention in this subsample. Perceived change in safety, and use of the infrastructure, were  
15  
16 therefore the only mediators included in the model for this subgroup (Figure 1b).  
17  
18  
19

### 20 21 22 *High-active subgroup*

23  
24 Similarly, in the high-active subgroup proximity to Connect2 was associated with use of the  
25  
26 infrastructure ( $OR = 1.79$ ,  $p = 0.001$ ) and use was associated with change in time spent walking and  
27  
28 cycling ( $\beta = 83.97$ ,  $p < 0.001$ ) (Additional File 4a, 4b). Proximity was associated with perceived  
29  
30 changes in visibility and infrastructure ( $0.06 \leq \beta \leq 0.10$ , both  $p < 0.08$ ), but the association with  
31  
32 perceived change in safety did not meet the criteria for inclusion (Additional File 4c). All three  
33  
34 perceived environmental changes met the criteria for a plausible direct association with use of  
35  
36 Connect2 ( $1.21 \leq OR \leq 1.58$ ,  $p < 0.09$ ), but not with change in time spent walking and cycling  
37  
38 (Additional File 4d, 4e). The association between perceived changes in infrastructure and visibility  
39  
40 also met the criteria for inclusion ( $\beta = 0.11$ ,  $p = 0.02$ ; Additional File 4f). Based on these results, we  
41  
42 developed the path model shown in Figure 1c.  
43  
44  
45  
46  
47  
48

### 49 **Step 3: Testing the intervention model**

50  
51 The model shown in Figure 1a was fitted in path analysis for the whole sample (Table 4). The  
52  
53 effect of proximity to the intervention on change in time spent walking and cycling was almost  
54  
55 entirely explained by an indirect path via use of the infrastructure (path 2, 90%), while the  
56  
57 remaining indirect paths that included perceived changes in infrastructure, safety or visibility  
58  
59  
60

together explained only 8% of the effect. Path analysis of the alternative models incorporating different causal ordering of the mediators gave very similar results (Additional File 2), as did path analysis of the models for the low- and high-active subgroups (Additional File 5).

**Table 4:** Contributions of different pathways to behaviour change

Path	$\beta$ (95% CI)	% of effect explained
Indirect via safety only (path 1)	0.21 (-0.68, 1.09)	0.4
Indirect via use only (path 2)	43.13 (22.09,	89.9
Indirect via infrastructure and use (path 3)	1.33 (0.03, 2.63)	2.8
Indirect via safety and use (path 4)	1.38 (-0.04, 2.81)	2.9
Indirect via visibility and use (path 5)	0.76 (-0.14, 1.65)	1.6
Indirect via infrastructure, visibility and use (path 6)	0.09 (-0.03, 0.20)	0.2
Direct (path 7)	1.09 (-9.63, 11.81)	2.2
Total (sum of paths 1-7)	47.99 (26.32,	100

Model shown in Figure 1 (a) fitted using path analysis in Mplus, adjusted for time spent walking and cycling at baseline and the demographic, socioeconomic and health characteristics shown in Table 2.

## DISCUSSION

### Principal findings

In this study we have refined and tested key components of a theoretical model linking the provision of new walking and cycling routes with changes in walking and cycling behaviour in local communities. In doing so, we have made both methodological and substantive contributions to the challenge of evaluating and understanding the effects of interventions to change the environmental determinants of health, which are understood to work through long and potentially complex casual pathways.<sup>13</sup> Having previously developed a provisional intervention model, we systematically identified the most plausible mediators, associations and causal ordering, refined, and formally tested the model using path analysis. We found that exposure to the intervention was associated with changes in the perceived supportiveness of the physical and social environments

1  
2 for walking and cycling, even after adjustment for baseline levels of those behaviours and other  
3 potential confounders. This suggests that the intervention was at least somewhat successful in  
4 changing those aspects of the environment. However, path analysis showed that the effects of the  
5 intervention on changes in walking and cycling were largely explained only by use of the new  
6 infrastructure, and that other explanatory pathways involving changes in cognitions relating to the  
7 environment explained only a small proportion of the effect. This overall finding was replicated in  
8 separate analyses restricted to participants with lower or higher levels of activity at baseline,  
9 although there were differences in the specific patterns of associations observed.  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21

### 22 **Strengths and limitations**

23  
24 In the context of an intervention to change environmental determinants of health, we have  
25 systematically identified the most important environmental mediators and their most plausible  
26 causal ordering, and tested and compared a series of mediating pathways, in order to improve our  
27 theory of how such interventions may work. Our study was conducted as a natural experiment  
28 using general population samples drawn from three contrasting communities, which confers a  
29 degree of external validity that may be lacking from some behavioural research conducted in less  
30 natural settings. A further strength lies in the specificity of the measures of perceptions of the  
31 physical environment, which were both specific to the area traversed by the intervention and  
32 hypothesised to change as a direct result of the intervention. Our approach to analysis was  
33 underpinned by a specific preliminary theoretical model for the intervention<sup>19</sup> and the pathways  
34 tested were consistent with the principles outlined in more general behavioural frameworks such as  
35 EnRG.<sup>28</sup> While the testing and refinement of theory in this way is commonly applied in the  
36 analysis of qualitative data,<sup>29</sup> it is less commonly (or explicitly) applied in the statistical analysis of  
37 quantitative data in public health research. This study therefore offers a methodological  
38 contribution to the challenge of evaluating and understanding complex public health interventions,  
39 an area in which both the theory of behaviour change and the methods for evaluation remain  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1 under-developed.<sup>29</sup> Partly for this reason, we used generous statistical criteria to identifying  
2 plausible pathways for further testing and we also tested some alternative model configurations,  
3 which showed that our assumptions about the causal ordering of mediators made little difference  
4 to the relative importance of the main pathways identified. We have tried to document our  
5 methods as clearly as possible in the hope that other researchers will adapt and refine our methods,  
6 investigate the replicability of our findings in other populations and settings, and explore the wider  
7 applicability of this approach in public health research.  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17

18  
19  
20 Nevertheless, this study had several important limitations. First, we restricted our analysis to  
21 participants with complete data on all mediators, which produced a sample for analysis that was  
22 somewhat younger and healthier than the main study sample<sup>17</sup>. This, together with the low initial  
23 response rate, means that our sample cannot be assumed to be representative of the local resident  
24 populations. Second, although our measures of perceptions of the physical environment were  
25 highly specific, we used more composite measures of perceptions of the social environment and of  
26 the behavioural outcomes, to ensure comparability with the main outcome evaluation and because  
27 the largest intervention effect was observed for the composite outcome of overall time spent  
28 walking and cycling.<sup>17</sup> We acknowledge the need for further investigation of more specific  
29 exposure-outcome relationships which may shed more light on how changes in specific  
30 behavioural outcomes come about.<sup>30</sup> Third, because changes in putative mediators and changes in  
31 behaviour were assessed over the same time period, we cannot be certain if changes in mediators  
32 led to changes in physical activity or vice versa. On the other hand, whereas most existing research  
33 on the mediators of the relationship between physical activity and the environment has explored  
34 only cross-sectional associations, which provide little basis for causal inference,<sup>31-33</sup> a key strength  
35 of our analysis is that it used longitudinal data from an intervention study in which environmental  
36 changes were known to have been introduced and could reasonably be assumed to have causally  
37 preceded the changes observed.<sup>11</sup>  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

### Understanding intervention mechanisms to strengthen the basis for causal inference

Our investigation not only provides greater understanding of the causal explanation of how behaviour change comes about as a consequence of an environmental intervention, but also provides a stronger basis for causal attribution. This was a natural experimental study in which participants were not randomised to allocation status, but were exposed to the intervention to a greater or lesser extent according to the geographical proximity of their home to the new infrastructure. In studies of this kind we can never be entirely sure that the analysis of the main effect is free from residual confounding by unobserved variables, which can neither be controlled for in analysis nor assumed to be balanced between groups as in a randomised controlled trial.<sup>34 35</sup> However, we have demonstrated a plausible, logical and parsimonious pathway linking geographical exposure to the intervention via individual use of the intervention to individual changes in walking and cycling behaviour, and we have shown that this mechanism explains the large majority of the effect of the intervention. This evidence for *how* an intervention achieves its effects (*causal explanation*) can be combined with the evidence for the size of those effects (*causal estimation*) reported elsewhere<sup>17</sup> to provide a stronger basis for valid causal inference.<sup>13</sup>

### Identifying modifiable perceptions of the physical and social environment

The rationale for selecting intervention sites for the Connect2 programme was to improve provision for local walking and cycling journeys in places where existing provision was poor. For example, the project in Cardiff involved providing a new traffic-free river crossing as an alternative to sharing space with motor vehicles on a busy road bridge or making a long detour,<sup>19</sup> factors which qualitative research with local informants identified as barriers to walking or cycling.<sup>18</sup> In our analysis, proximity to and use of the intervention both showed significant associations with perceived changes in infrastructure and safety for walking and cycling and with the perceived visibility of those behaviours in the neighbourhood. This provides some evidence



1  
2 that the Connect2 programme was successful in influencing these characteristics of the  
3 environment, and that these changes may have contributed to people taking up the opportunity to  
4 use the new infrastructure. Restricting the analysis to participants with a higher level of activity at  
5 baseline revealed a similar pattern of associations to that observed in the whole sample, whereas in  
6 the low-active subgroup a perceived change in safety was the only environmental mediator found  
7 to be associated with both exposure and use. Consistent with findings from some cross-sectional  
8 and longitudinal studies,<sup>36</sup> this suggests that improving safety – reflected in this study by survey  
9 questions about safety from crime or antisocial behaviour, as well as safety from traffic – may be  
10 particularly important in promoting the use of walking and cycling routes among those with the  
11 most capacity to benefit from an increase in physical activity.  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26

### 27 **The role of behaviour-specific cognitions in behaviour change**

28 Despite the fact that perceived changes in the physical and social environment were reported by  
29 people living in the areas served by the Connect2 projects and associated with use of the new  
30 routes, we found that pathways between intervention exposure and behaviour change involving  
31 these perceived changes explained a very small percentage of the intervention effect, 90% of  
32 which was accounted for by use of the intervention alone. This may appear a slightly unexpected  
33 finding, given the body of cross-sectional evidence suggesting a relationship between physical  
34 activity behaviours and the perceived supportiveness of the environment.<sup>8 9</sup>  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46

47 Perceived environmental changes were only weakly associated with changes in time spent walking  
48 and cycling, suggesting that they played a relatively small part in determining overall behaviour  
49 change in the sample. Importantly, the largest contributor to the increase in overall time spent  
50 walking and cycling was an increase in recreational walking,<sup>17</sup> whereas at baseline perceptions of  
51 the environment were generally more strongly associated with walking or cycling for transport  
52 than with walking or cycling for recreation.<sup>37</sup> The latter finding is consistent with existing  
53  
54  
55  
56  
57  
58  
59  
60

1 literature in which attributes of the environment have been found to have mixed patterns of  
2 associations with walking and cycling, and with recreational and transport activities.<sup>8 9</sup> It is  
3 therefore possible that stronger evidence of mediation may have been found for other unmeasured  
4 environmental attributes more closely related to recreational activities (or indeed for other  
5 psychological constructs such as confidence, intention or self-efficacy, which were not the focus of  
6 this study).  
7  
8  
9  
10  
11  
12  
13

14  
15  
16  
17 An alternative interpretation of the weak evidence for the mediating role of behaviour-specific  
18 cognitions in this study is that it supports the notion of more automatic, unconscious processes  
19 linking environmental change with behaviour change. Behavioural scientists have described how  
20 behaviour may be determined by a more reflective, goal-orientated system on the one hand or by a  
21 more automatic, affective system on the other,<sup>38</sup> and Kremers and colleagues have specifically  
22 referred to both ‘mediated’ and ‘unmediated’ pathways in the context of the influence of the  
23 environment on energy-related behaviours.<sup>28</sup> Our findings could be regarded as consistent with,  
24 although certainly not proof of, the hypothesis that physical activity behaviour change can be  
25 promoted by altering relevant environmental cues — sometimes referred to as changing choice  
26 architecture<sup>39</sup> or ‘nudging’<sup>40</sup>— without explicitly encouraging the target behaviours or directly  
27 addressing people’s perceptions and other cognitions relating to them.<sup>41</sup> Indeed, the fact that  
28 behaviour change in this study was strongly associated with proximity to and use of the  
29 infrastructure, but only weakly associated with people’s perceptions of how the environment had  
30 changed, may suggest that the physical improvement of the environment itself — rather than the  
31 modification of people’s perceptions of their environment — was the key to the effectiveness of  
32 the intervention.  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51

### 52 53 54 55 **Implications for future research** 56 57 58 59 60

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

As many authors have pointed out, few studies have evaluated the effects of environmental approaches to changing population physical activity behaviour, and even fewer have gone beyond estimating their effects to investigate the mechanisms underlying the (in)effectiveness of interventions.<sup>5 10 11 42 43</sup> Complementary evidence of effects and mechanisms will help strengthen the case for causal inference, particularly in a field in which randomised controlled trials are rarely feasible.<sup>12 13</sup> More work is required to refine the hypotheses about how specific interventions may work and to generate improved measures to reflect the proposed mechanisms. These may include objective measures of the nature, extent, timing and quality of environmental change<sup>44</sup>, as well as detailed individual-level measures of the ‘dose’ of intervention received — such as exposure to and use of new environments<sup>45</sup> — and of how the intervention is received and interpreted. Improved measures of this kind will enable the hypothesised pathways to behaviour change to be tested — and preferably reported as transparently as possible, as recommended by the authors of a recent review<sup>46</sup> — in order to identify the most promising strategies for future interventions to change the environmental determinants of health.

## CONCLUSIONS

Local residents’ perceptions of the supportiveness of the physical and social environment for walking and cycling were changed after the construction of new infrastructure in their communities. However, the effect of the intervention on overall walking and cycling was largely explained by a simple causal pathway involving use of the new routes, and other explanatory pathways involving changes in cognitions relating to the environment explained only a small proportion of the overall effect. These findings imply that cognitive processing of environmental conditions may play a limited role in behaviour change, and that high-quality changes to the physical environment itself — rather than changing people’s perceptions of their environment — may be the key to the effectiveness of this type of intervention. Studies of how interventions lead

1  
2 to behaviour change should complement those concerned with estimating their effects in  
3  
4 supporting valid causal inference in public health research.  
5  
6  
7

8  
9 **Contributors:** JP and DO conception and design of the analysis. JP analysed the data. Both  
10 interpreted the data, drafted the article and revised it critically for important intellectual content,  
11 and approved the final version of the submitted manuscript.  
12  
13

14  
15 **Acknowledgements:** This article was written on behalf of the iConnect consortium  
16 (<http://www.icconnect.ac.uk>: Christian Brand, Fiona Bull, Ashley Cooper, Andy Day, Nanette  
17 Mutrie, David Ogilvie, Jane Powell, John Preston, and Harry Rutter). The iConnect consortium is  
18 funded by the Engineering and Physical Sciences Research Council (EPSRC) [grant  
19 EP/G00059X/1], Jenna Panter is funded by a National Institute for Health Research (NIHR) Post-  
20 Doctoral Fellowship [PDF 2012-05-157], and David Ogilvie is supported by the Medical Research  
21 Council (MRC) [Unit programme number MC\_UU\_12015/6]. This article presents independent  
22 research in which the funders had no involvement in the study design; the collection, analysis, and  
23 interpretation of data; the writing of the article; or the decision to submit the article for publication.  
24 The views expressed are those of the authors and not necessarily those of the NHS, the NIHR, the  
25 Department of Health or the other funders. We thank the study participants for their cooperation  
26 and the study team led by Karen Ghali for managing data collection.  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54

55 **Competing interests:** None.  
56  
57

58 **Data sharing:** For further information please refer to the MRC Epidemiology Unit data sharing  
59 portal at <http://epi-meta.medschl.cam.ac.uk>.  
60

## References

1. Das P, Horton R. Rethinking our approach to physical activity. *Lancet* 2012;**380**(9838):189-90.
2. Saunders LE, Green JM, Pettecrew MP, et al. What Are the Health Benefits of Active Travel? A Systematic Review of Trials and Cohort Studies. *PLoS ONE* 2013;**8**(8):e69912.
3. Appleyard D. *Livable Streets*: University of California Press, 1982.
4. Woodcock J, Edwards P, Tonne C, et al. Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. *Lancet* 2009;**374**(9705):1930-43.
5. Ogilvie D, Egan M, Hamilton V, et al. Promoting walking and cycling as an alternative to using cars: systematic review. *BMJ* 2004;**329**:763-66.
6. Ogilvie D, Foster C, Rothnie H, et al. Interventions to promote walking: systematic review. *BMJ* 2007;**334**:1204-07.
7. Yang L, McMinn A, Sahlqvist S, et al. Interventions to promote cycling: systematic review. *BMJ* 2010;**341**:c5293.
8. Saelens B, Sallis J, Frank L. Environmental correlates of walking and cycling: Findings from the transportation, urban design, and planning literatures. *Ann Behav Med* 2003;**25**:80 - 91.
9. Saelens BE, Handy S. Built environment correlates of walking: A review. *Medicine and Science in Sports and Exercise* 2008;**40**(7):550-66.
10. Bauman AE, Reis RS, Sallis JF, et al. Correlates of physical activity: why are some people physically active and others not? *Lancet* 2012;**380**(9838):258-71.
11. McCormack G, Shiell A. In search of causality: a systematic review of the relationship between the built environment and physical activity among adults. *Int J Behav Nutr Phys Act* 2011;**8**(1):125.
12. Briggs DC. Comments on Slavin: Synthesizing Causal Inferences. *Educational Researcher* 2008;**37**(1):15-22.
13. Victora CG, Habicht J-P, Bryce J. Evidence-Based Public Health: Moving Beyond Randomized Trials. *American journal of public health* 2004;**94**(3):400-05.
14. Sallis JF, Owen N. Ecological models of health behavior. In: Glanz K, Lewis FM, Rimer BK, eds. *Health Behaviour and Health Education: Theory, Research, and Practice*. San Francisco: Jossey-Bass, 2002:462-84.
15. Rychetnik L, Frommer M, Hawe P, et al. Criteria for evaluating evidence on public health interventions. *Journal of Epidemiology and Community Health* 2002;**56**(2):119-27.
16. Ogilvie D, Bull F, Powell J, et al. An applied ecological framework for evaluating infrastructure to promote walking and cycling: the iConnect study. *Am J Public Health* 2011;**101**:473-81.
17. Goodman A, Sahlqvist S, Ogilvie D, et al. New walking and cycling routes and increased physical activity: one- and two-year findings from the UK iConnect study. *Am J Public Health* 2014;**104**:e38-e46.
18. Sahlqvist S, Goodman A, Jones T, et al. Understanding the effects of new walking and cycling infrastructure: findings from the UK iConnect study *Int J Behav Nutr Phys Act Under review*.
19. Ogilvie D, Bull F, Cooper A, et al. Evaluating the travel, physical activity and carbon impacts of a 'natural experiment' in the provision of new walking and cycling infrastructure: methods for the core module of the iConnect study. *BMJ Open* 2012;**2**:e000694.

20. Adams E, Goad M, S. S, et al. Reliability and validity of the transport and physical activity questionnaire (TPAQ) for assessing physical activity behaviour. *PLoS One* 2014;**9**(9):e107039.
21. World Health Organisation. Obesity: preventing and managing the global epidemic. Geneva: World Health Organisation, 2000.
22. Pedhazur EJ. *Multiple regression in behavioral research: explanation and prediction (Third Edition)*. Fort Worth, Texas, USA Harcourt Brace., 1997.
23. Bartlett M. The statistical conception of mental factors. *British Journal of Psychology* 1937;**28**(97-104).
24. Acock A. *A gentle introduction to Stata (Second Edition)*. College Station, Texas: Stata Press, 2008.
25. Muthén L, Muthén B. *Mplus User's Guide*. Seventh Edition. Los Angeles, CA: Muthén & Muthén, 2012.
26. Golob TF. Structural equation modeling for travel behavior research. *Transportation Research Part B: Methodological* 2003;**37**(1):1-25.
27. Goodman A, Sahlqvist S, Ogilvie D. Who uses new walking and cycling infrastructure and how? Longitudinal results from the UK iConnect study. *Preventive Medicine* 2013;**57**(5):518-24.
28. Kremers SPJ, Bruijn G, Visscher TLS, et al. Environmental influences on energy balance-related behaviors: A dual-process view. *Int J Behav Nutr Phys Act* 2006;**3**:9.
29. Pope C, Ziebland S, Mays N. Analysing qualitative data. *BMJ* 2000;**320**(7227):114-16.
30. Giles-Corti B, Timperio A, Bull F, et al. Understanding physical activity environmental correlates: increased specificity for ecological models. *Exercise and Sports Science Reviews* 2005;**33**:175-81.
31. Koohsari MJ, Sugiyama T, Lamb KE, et al. Street connectivity and walking for transport: Role of neighborhood destinations. *Preventive medicine* 2014;**66**:118-22.
32. McCormack G, Spence J, Berry T, et al. Does perceived behavioral control mediate the association between perceptions of neighborhood walkability and moderate- and vigorous-intensity leisure-time physical activity? *Journal of physical activity & health* 2009;**6**(5):657-66.
33. Timperio AF, van Stralen MM, Brug J, et al. Direct and indirect associations between the family physical activity environment and sports participation among 10-12 year-old European children: testing the EnRG framework in the ENERGY project. *Int J Behav Nutr Phys Act* 2013;**10**:15.
34. Cousens S, Hargreaves J, Bonell C, et al. Alternatives to randomisation in the evaluation of public-health interventions: statistical analysis and causal inference. *Journal of Epidemiology and Community Health* 2011;**65**(7):576-81.
35. Craig P, Cooper C, Gunnell D, et al. Using natural experiments to evaluate population health interventions: new Medical Research Council guidance. *J Epidemiol Community Health* 2012;**66**(12):1182-6.
36. Foster S, Knuiman M, Hooper P, et al. Do changes in residents' fear of crime impact their walking? Longitudinal results from RESIDE. *Preventive Medicine* 2014;**62**(0):161-66.
37. Adams E, Goodman A, Sahlqvist S, et al. Correlates of walking and cycling for transport and recreation: factor structure, reliability and behavioural associations of the perceptions of

- 1  
2 the environment in the neighbourhood scale (PENS). *International Journal of Behavioral*  
3 *Nutrition and Physical Activity* 2013;**10**(1):87.
- 4  
5 38. Strack F, Deutsch R. Reflective and Impulsive Determinants of Social Behavior. *Personality*  
6 *and Social Psychology Review* 2004;**8**(3):220-47.
- 7  
8 39. Hollands G, Shemilt I, Marteau T, et al. Altering micro-environments to change population  
9 health behaviour: towards an evidence base for choice architecture interventions. *BMC*  
10 *Public Health* 2013;**13**(1):1218.
- 11  
12 40. Thaler R, Sunstein C. *Nudge: Improving decisions about health, wealth and happiness*. New  
13 Haven: Yale University Press 2008.
- 14  
15 41. Owen N, Humpel N, Leslie E, et al. Understanding environmental influences on walking;  
16 Review and research agenda. *Am J Prev Med* 2004;**27**:67 - 76.
- 17  
18 42. Excellence NifHaC. Walking and cycling: local measures to promote walking and cycling as  
19 forms of travel or recreation. London: National Institute for Health and Clinical  
20 Excellence, 2012.
- 21  
22 43. Pawson R, Tilley N. *Realistic Evaluation*. London, UK: Sage, 1997.
- 23  
24 44. Hooper P, Giles-Corti B, Knuiiman M. Evaluating the implementation and active living  
25 impacts of a state government planning policy designed to create walkable neighborhoods  
26 in Perth, Western Australia. *American journal of health promotion : AJHP* 2014;**28**(3  
27 Suppl):S5-18.
- 28  
29 45. Humphreys D, Panter J, S. S, et al. A framework for considering exposure in place-based  
30 natural experimental studies in public health. *Social Science and Medicine* Under review.
- 31  
32 46. Rhodes R, Pfaeffli L. Mediators of physical activity behaviour change among adult non-  
33 clinical populations: a review update. *International Journal of Behavioral Nutrition and*  
34 *Physical Activity* 2010;**7**(1):37.
- 35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

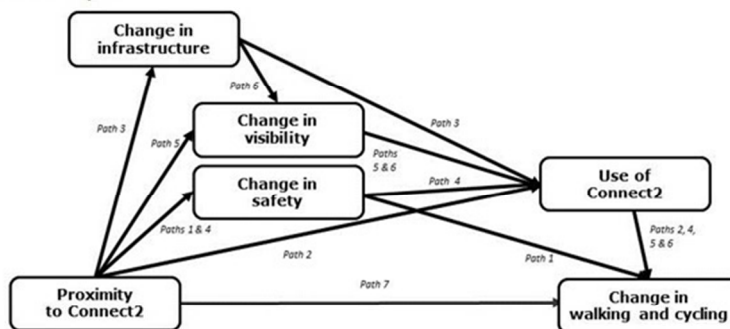
**Figure legend**

**Figure 1: Path models fitted in Mplus**

For peer review only

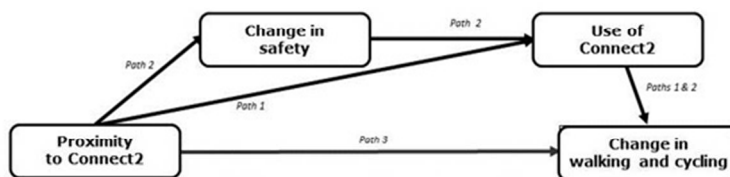


(a) Whole sample



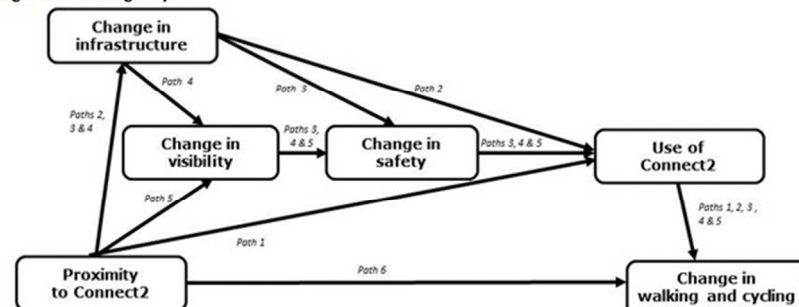
Path 1: indirect via safety only; path 2: indirect via use only; path 3: indirect via infrastructure and use; path 4: indirect via safety and use; path 5: indirect via visibility and use; path 6: indirect via infrastructure, visibility and use; path 7: direct path.

(b) Low-active subgroup



Path 1: indirect via use only; path 2: indirect via safety and use; path 3: direct path.

(c) High-active subgroup



Path 1: indirect via use only; path 2: indirect via infrastructure and use; path 3: indirect via infrastructure, safety and use; path 4: indirect via infrastructure, visibility, safety and use; path 5: visibility, safety and use; path 6: direct path.

183x235mm (96 x 96 DPI)

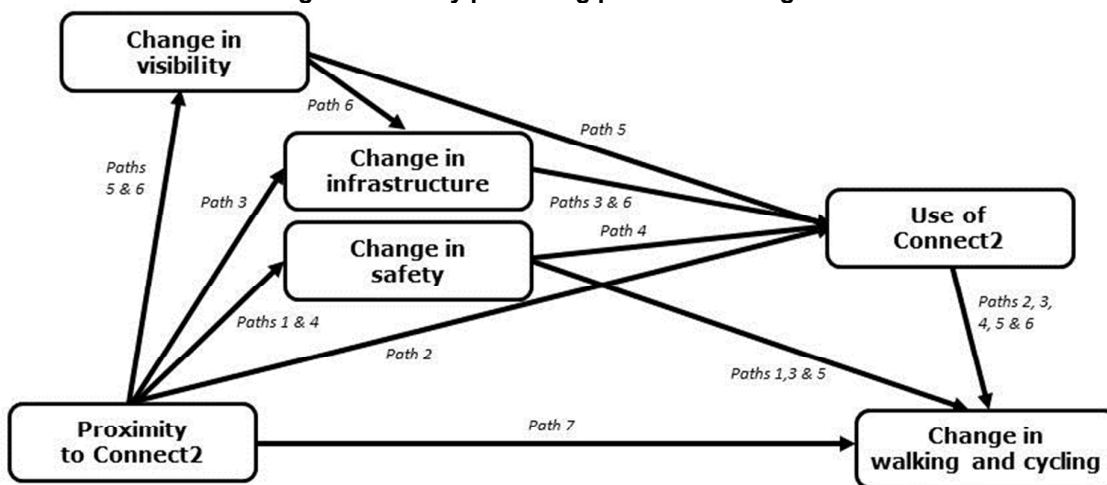
1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

**Additional File 1: Factor analysis of perceived physical environmental items at baseline and follow-up**

<b>Baseline</b>	Factor 1: 'Infrastructure'	Factor 2: 'Safety'	
Safety for walking	0.285	0.773	
Safety for cycling	0.256	0.794	
Pavements for walking	0.673	0.308	
Special lanes for cycling	0.748	0.256	
Pleasant	0.546	0.498	
Low crime	-0.209	0.715	
Lighting	0.770	-0.069	<i>n=1306</i>
Eigenvalue	3.01	1.23	
<b>Follow-up</b>			
Safety for walking	0.268	0.818	
Safety for cycling	0.258	0.804	
Pavements for walking	0.754	0.198	
Special lanes for cycling	0.759	0.236	
Pleasant	0.645	0.399	
Low crime	-0.066	0.763	
Lighting	0.763	0.006	<i>n=1310</i>
Eigenvalue	3.18	1.24	

**Additional File 2: Results for alternative models with different ordering of mediators**

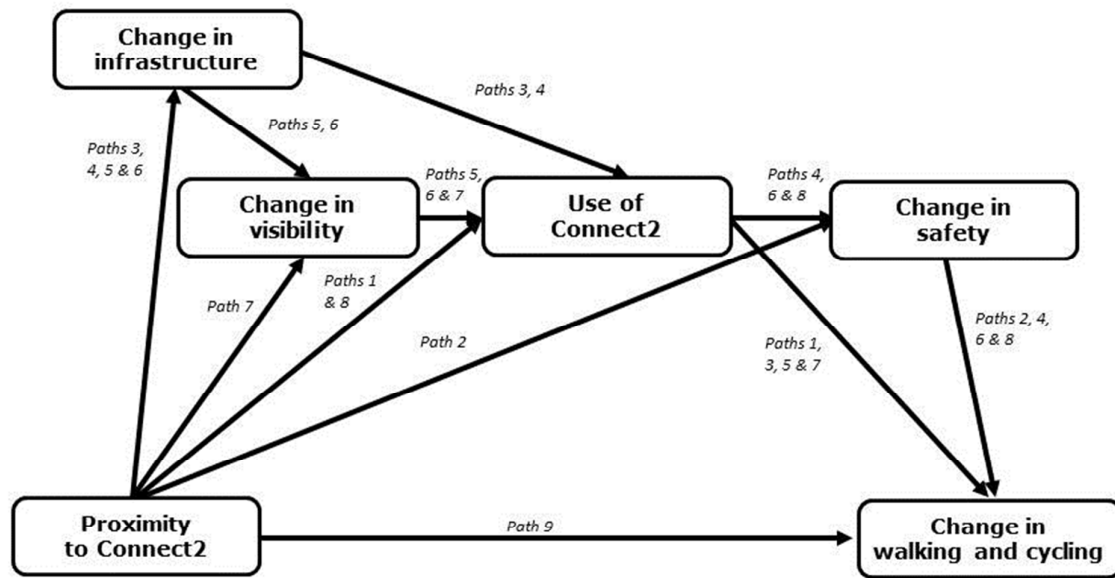
**Alternative 1: Perceived change in visibility preceding perceived change in infrastructure**



Path	$\beta$ (95% CI)	% of effect explained
Indirect via safety only (path 1)	2.25 (-7.14, 11.63)	4.5
Indirect via use only (path 2)	43.13 (22.09, 64.17)	86.2
Indirect via infrastructure and use (path 3)	1.26 (0.00, 2.51)	2.6
Indirect via safety and use (path 4)	1.38 (-0.04, 2.81)	2.8
Indirect via visibility and use (path 5)	0.84 (-0.10, 1.78)	1.6
Indirect via visibility, infrastructure and use (path 6)	0.08 (-0.03, 0.18)	0.2
Direct (path 7)	1.09 (-9.63, 11.81)	2.1
Total (sum of paths 1-7)	50.03 (27.61, 72.44)	100

**Model shown above fitted** using path analysis in Mplus, adjusted for time spent walking and cycling at baseline and the demographic, socioeconomic and health characteristics shown in Table 2

## Alternative 2: Perceived change in safety as a consequence of using the infrastructure



Path	$\beta$ (95% CI)	% of effect explained
Indirect via use only (path 1)	43.72 (22.47 to 64.96)	91.38
Indirect via safety only (path 2)	0.06 (-0.24 to 0.35)	0.11
Indirect via infrastructure and use (path 3)	1.4 (0.07 to 2.74)	2.93
Indirect via infrastructure, use and safety (path 4)	0.02 (-0.08 to 0.13)	0.05
Indirect via infrastructure, visibility and use (path 5)	0.07 (-0.02 to 0.15)	0.14
Indirect via infrastructure, visibility, use and safety (path 6)	0 (0 to 0.01)	0.01
Indirect via visibility and use (path 7)	0.78 (-0.13 to 1.69)	1.63
Indirect via use and safety (path 8)	0.69 (-2.48 to 3.87)	1.45
Direct (path 9)	1.1 (-9.62 to 11.82)	2.3
Total (sum of paths)	47.84 (26.62 to 69.06)	100

**Model shown above fitted** using path analysis in Mplus, adjusted for time spent walking and cycling at baseline and the demographic, socioeconomic and health characteristics shown in Table 2

## Additional File 3: Associations in low-active subgroup

<b>(a) Associations between proximity to and use of intervention</b>		
<b>Independent variable: Residential proximity to intervention (km)</b>		
<b>Dependent variable</b>	<b>OR (95% CI)</b>	<b>p</b>
Use of intervention (yes/no)	2.05 (1.68, 2.50)	0.001
<b>(b) Associations between use of intervention and changes in walking and cycling</b>		
<b>Independent variable: Use of intervention (yes/no)</b>		
<b>Dependent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in time spent walking and cycling (min/week)	62.96 (29.20, 96.71)	0.001
<b>(c) Associations between proximity to intervention and perceived environmental changes</b>		
<b>Independent variable: Residential proximity to intervention (km)</b>		
<b>Dependent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	0.05 (-0.02, 0.12)	0.153
Change in safety	0.08 (0.01, 0.15)	0.030
Change in visibility	0.01 (-0.05, 0.07)	0.804
<b>(d) Associations between perceived environmental changes and use of intervention</b>		
<b>Dependent variable: Use of intervention (yes/no)</b>		
<b>Independent variable</b>	<b>OR (95% CI)</b>	<b>p</b>
Change in infrastructure	1.12 (0.90, 1.40)	0.308
Change in safety	1.42 (1.12, 1.78)	0.001
Change in visibility	1.14 (0.91, 1.42)	0.240
<b>(e) Associations between perceived environmental changes and change in walking and cycling</b>		
<b>Dependent variable: Change in time spent walking and cycling (min/week)</b>		
<b>Independent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	-12.69 (-28.99, 3.61)	0.130
Change in safety	9.15 (-6.66, 24.97)	0.260
Change in visibility	-12.27 (-27.74, 3.20)	0.120
<b>(f) Associations between perceived environmental changes</b>		
<b>Dependent variable: Changes in visibility</b>		
<b>Independent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	0.02 (-0.06, 0.11)	0.596
Change in safety	0.04 (-0.04, 0.12)	0.341
<b>Dependent variable: Change in safety</b>		
<b>Independent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	-0.11 (-0.20, -0.01)	0.020

Linear or logistic regression models as appropriate adjusted for time spent walking and cycling at baseline and the demographic, socioeconomic and health characteristics shown in Table 2. Proximity was modelled as the negative of the distance between home and the nearest access point to the 'greater Connect2 project' including feeder routes. Each row represents a separate model which was not adjusted for the other mediators.

## Additional File 4: Associations in high-active subgroup

<b>(a) Associations between proximity to and use of intervention</b>		
<b>Independent variable: Residential proximity to intervention (km)</b>		
<b>Dependent variable</b>	<b>OR (95% CI)</b>	<b>p</b>
Use of intervention (yes/no)	1.79 (1.51, 2.11)	0.001
<b>(b) Associations between use of intervention and change in walking and cycling</b>		
<b>Independent variable: Use of intervention (yes/no)</b>		
<b>Dependent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>P</b>
Change in time spent walking and cycling (min/week)	83.97 (34.65, 133.20)	0.001
<b>(c) Associations between proximity to intervention and perceived environmental changes</b>		
<b>Independent variable: Residential proximity to intervention (km)</b>		
<b>Dependent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	0.06 (-0.01, 0.12)	0.076
Change in safety	0.00 (-0.07, 0.06)	0.951
Change in visibility	0.10 (0.04, 0.16)	0.001
<b>(d) Associations between perceived environmental changes and use of intervention</b>		
<b>Dependent variable: Use of intervention (yes/no)</b>		
<b>Independent variable</b>	<b>OR (95% CI)</b>	<b>p</b>
Change in infrastructure	1.36 (1.08, 1.72)	0.008
Change in safety	1.21 (0.97, 1.52)	0.089
Change in visibility	1.58 (1.27, 1.95)	0.001
<b>(e) Associations between perceived environmental changes and change in walking and cycling</b>		
<b>Dependent variable: Change in time spent walking and cycling (min/week)</b>		
<b>Independent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	5.02 (-20.08, 30.12)	0.695
Change in safety	9.00 (-16.76, 34.76)	0.493
Change in visibility	3.66 (-21.05, 28.37)	0.771
<b>(f) Associations between physical and social environmental changes</b>		
<b>Dependent variable: Change in visibility of walking and cycling</b>		
<b>Independent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	0.11 (0.02, 0.20)	0.020
Change in safety	0.03 (-0.06, 0.12)	0.580
<b>Dependent variable: Change in safety</b>		
<b>Independent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	0.06 (-0.03, 0.15)	0.188

Linear or logistic regression models as appropriate adjusted for time spent walking and cycling at baseline and the demographic, socioeconomic and health characteristics shown in Table 2. Proximity was modelled as the negative of the distance between home and the nearest access point to the 'greater Connect2 project' including feeder routes. Each row represents a separate model which was not adjusted for the other mediators.

**Additional File 5: Contributions of different pathways to behaviour change in those with (a) a low and (b) a high level of walking and cycling at baseline**

	<b>β 95%CI</b>
<b>(a) Low-active subgroup</b>	
Indirect via use only (path 1)	40.0 (10.17, 69.92)
Indirect via safety and use (path 2)	2.3 (-0.28, 4.87)
Direct (path 3)	0.0 (-13.28, 12.74)
Total (sum of paths 1-3)	42.3 (12.4, 71.74)
<b>(b) High-active subgroup</b>	
Indirect via use only (path 1)	48.62 (15.66 to 81.58)
Indirect via infrastructure and use (path 2)	0.22 (-0.5 to 0.94)
Indirect via infrastructure, safety and use (path 3)	0 (0 to 0)
Indirect via infrastructure, visibility, safety and use (path 4)	0 (-0.12 to 0.12)
Indirect via visibility, safety and use (path 5)	0 (-0.35 to 0.35)
Direct (path 6)	1.1 (-17.09 to 19.29)
Total (sum of paths 1-6)	49.94 (17.58 to 82.3)

**Models shown in Figures 1 (b) and (c) respectively fitted** using path analysis in Mplus, adjusted for time spent walking and cycling at baseline and the demographic, socioeconomic and health characteristics shown in Table 2.

STROBE Statement—Checklist of items that should be included in reports of cohort studies

Section/Topic	Item #	Recommendation	Reported on page #
Title and abstract	1	(a) Indicate the study’s design with a commonly used term in the title or the abstract	1
		(b) Provide in the abstract an informative and balanced summary of what was done and what was found	2
<b>Introduction</b>			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	3-4
Objectives	3	State specific objectives, including any prespecified hypotheses	5
<b>Methods</b>			
Study design	4	Present key elements of study design early in the paper	5
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	5-6
Participants	6	(a) Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up	5-6
		(b) For matched studies, give matching criteria and number of exposed and unexposed	N/A
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	6-9
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	6-9
Bias	9	Describe any efforts to address potential sources of bias	N/A
Study size	10	Explain how the study size was arrived at	11
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	11
Statistical methods	12	(a) Describe all statistical methods, including those used to control for confounding	11
		(b) Describe any methods used to examine subgroups and interactions	11
		(c) Explain how missing data were addressed	11
		(d) If applicable, explain how loss to follow-up was addressed	N/A
		(e) Describe any sensitivity analyses	N/A
<b>Results</b>			



Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	11
		(b) Give reasons for non-participation at each stage	11
		(c) Consider use of a flow diagram	N/A
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	13
		(b) Indicate number of participants with missing data for each variable of interest	13
		(c) Summarise follow-up time (eg, average and total amount)	5
Outcome data	15*	Report numbers of outcome events or summary measures over time	N/A
Main results	16	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	15
		(b) Report category boundaries when continuous variables were categorized	13
		(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	N/A
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	17, 18 and Additional file
<b>Discussion</b>			
Key results	18	Summarise key results with reference to study objectives	19
<b>Limitations</b>			
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	21-22
Generalisability	21	Discuss the generalisability (external validity) of the study results	20
<b>Other information</b>			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	26

\*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

**Note:** An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at <http://www.plosmedicine.org/>, Annals of Internal Medicine at <http://www.annals.org/>, and Epidemiology at <http://www.epidem.com/>). Information on the STROBE Initiative is available at [www.strobe-statement.org](http://www.strobe-statement.org).

# BMJ Open

## Theorising and testing environmental pathways to behaviour change: natural experimental study of the perception and use of new infrastructure to promote walking and cycling in local communities

Journal:	<i>BMJ Open</i>
Manuscript ID:	bmjopen-2015-007593.R1
Article Type:	Research
Date Submitted by the Author:	05-May-2015
Complete List of Authors:	Panter, Jenna; University of Cambridge, UKCRC Centre for Diet and Activity Research (CEDAR) Ogilvie, David; University of Cambridge, UKCRC Centre for Diet and Activity Research (CEDAR)
<b>Primary Subject Heading</b>:	Public health
Secondary Subject Heading:	Epidemiology
Keywords:	EPIDEMIOLOGY, PREVENTIVE MEDICINE, PUBLIC HEALTH

SCHOLARONE™  
Manuscripts

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1 **Theorising and testing environmental pathways to behaviour change: natural**  
2 **experimental study of the perception and use of new infrastructure to promote walking**  
3 **and cycling in local communities**

4  
5 **Authors:** Jenna Panter and David Ogilvie on behalf of the iConnect consortium

6 **Affiliation:** Medical Research Council Epidemiology Unit and UKCRC Centre for Diet and  
7 Activity Research (CEDAR), University of Cambridge, Box 285, Cambridge Biomedical  
8 Campus, Cambridge, CB2 0QQ, UK.

9 **Corresponding author information:** Jenna Panter, Medical Research Council  
10 Epidemiology Unit and UKCRC Centre for Diet and Activity Research (CEDAR), University  
11 of Cambridge, Box 285, Cambridge Biomedical Campus, Cambridge, CB2 0QQ, UK.  
12 Phone: +44 (0)1223 746884. Fax: +44 (0)1223 330316. Email: [jenna.panter@mrc-](mailto:jenna.panter@mrc-epid.cam.ac.uk)  
13 [epid.cam.ac.uk](mailto:jenna.panter@mrc-epid.cam.ac.uk)

14  
15 **Key words:** causality, environment design, evaluation, health promotion, physical activity

16

1  
2  
3 17 **ABSTRACT:**  
4

5 18 **Objective:** Some studies have assessed the effectiveness of environmental interventions to  
6  
7 19 promote physical activity, but few have examined how such interventions work. We  
8  
9 20 investigated the environmental mechanisms linking an infrastructural intervention with  
10  
11 21 behaviour change.  
12

13  
14 22 **Design:** Natural experimental study.  
15

16 23 **Setting:** Three UK municipalities (Southampton, Cardiff and Kenilworth).  
17

18 24 **Participants:** Adults living within 5km of new walking and cycling infrastructure.  
19

20 25 **Intervention:** Construction or improvement of walking and cycling routes. Exposure to the  
21  
22 26 intervention was defined in terms of residential proximity.  
23

24 27 **Outcome measures:** Questionnaires at baseline and two-year follow-up assessed perceptions  
25  
26 28 of the supportiveness of the environment, use of the new infrastructure, and walking and  
27  
28 29 cycling behaviours. Analysis proceeded via factor analysis of perceptions of the physical  
29  
30 30 environment (step 1) and regression analysis to identify plausible pathways involving  
31  
32 31 physical and social environmental mediators and refine the intervention theory (step 2) to a  
33  
34 32 final path analysis to test the model (step 3).  
35  
36

37 33 **Results:** Participants who lived near and used the new routes reported improvements in their  
38  
39 34 perceptions of provision and safety. However, path analysis (step 3, n=967) showed that the  
40  
41 35 effects of the intervention on changes in time spent walking and cycling were largely (90%)  
42  
43 36 explained by a simple causal pathway involving use of the new routes, and other pathways  
44  
45 37 involving changes in environmental cognitions explained only a small proportion of the  
46  
47 38 effect.  
48

49 39 **Conclusions:** Physical improvement of the environment itself was the key to the  
50  
51 40 effectiveness of the intervention, and seeking to change people's perceptions may be of  
52  
53 41 limited value. Studies of how interventions lead to population behaviour change should  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 42 complement those concerned with estimating their effects in supporting valid causal  
4  
5 43 inference.  
6  
7  
8 44

9  
10 45 **Strengths and limitations of this study**

- 11 46 • In the context of an intervention to change environmental determinants of health, we  
12  
13 systematically identified the environmental mediators of changes in walking and  
14 47  
15  
16 48 cycling in a population-based sample.  
17  
18 49 • Such evidence for *how* an intervention achieves its effects (*causal explanation*) can be  
19  
20 combined with the evidence for the size of those effects (*causal estimation*) to provide  
21 50  
22 a stronger basis for causal inference.  
23 51  
24  
25 52 • We cannot be certain if changes in mediators led to changes in physical activity, or  
26  
27 vice versa, as these were assessed over the same time period. However, most existing  
28 53  
29 research on the mediators of the relationship between physical activity and the  
30 54  
31 environment has been limited to cross-sectional associations, whereas our analysis  
32 55  
33 used longitudinal data from an intervention study.  
34 56  
35  
36 57 • We restricted our analysis to participants with complete data on all mediators, which  
37  
38 produced a sample for analysis that was somewhat younger and healthier than the  
39 58  
40 main study sample.  
41 59  
42  
43 60 • Stronger evidence of mediation might have been found for other unmeasured  
44  
45 environmental attributes more closely related to recreational activities, or for other  
46 61  
47 psychological and social constructs such as confidence, intention, self-efficacy or  
48 62  
49 norms.  
50 63  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

## 64 INTRODUCTION

### 66 Physical activity and the environment

67 Promoting physical activity is a public health priority,<sup>[1]</sup> and walking and cycling are  
68 potential targets for intervention strategies because they are relatively easy to integrate into  
69 daily life and may confer substantial individual health benefits<sup>[2]</sup> and wider social and  
70 environmental co-benefits.<sup>[3,4]</sup> However, efforts to encourage walking and cycling at the  
71 population level have met with modest success to date.<sup>[5-7]</sup> It is argued that changing the  
72 environment may be required to produce broader and more sustained effects, but this is  
73 mostly based on evidence from cross-sectional observational studies. These suggest that  
74 factors such as distance to destinations, density and land use mix may be important influences  
75 on walking and cycling,<sup>[8,9]</sup> but there are few longitudinal studies examining the  
76 environmental determinants of behaviour change or evaluating the impact of environmental  
77 changes.<sup>[5-11]</sup> While these latter types of study are gradually shifting the focus of research  
78 from correlation towards causation, they sometimes report null associations for  
79 environmental attributes found to be significant in cross-sectional studies.<sup>[11]</sup> Even if well  
80 designed studies have provided a relatively unbiased estimate of the effect size for an  
81 environmental intervention (*causal estimation*), some authors argue that valid causal  
82 inference in public health also depends on showing *how* an intervention brings about the  
83 outcomes attributed to it (*causal explanation*).<sup>[12,13]</sup>

### 85 In search of causal explanation for environmental interventions

86 Socio-ecological models postulate that intra-personal, inter-personal, and community-level  
87 environmental factors are important influences on health behaviours, and these have been  
88 shown to be important for physical activity.<sup>[14]</sup> However these models generally provide a

1  
2  
3 89 broad framework indicating the existence of such influences at multiple levels, rather than  
4  
5 90 considering *specifically* how behaviour is postulated to change in response to environmental  
6  
7 91 changes. Understanding such mechanisms could be expected to clarify the significance and  
8  
9  
10 92 role of specific factors along the putative causal pathway linking environmental change to  
11  
12 93 physical activity behaviour change,<sup>[12,13,15]</sup> but few studies have attempted to do this.<sup>[11]</sup> This  
13  
14 94 may reflect the fact that the causal pathways for public health interventions can be long and  
15  
16 95 complex.<sup>[13]</sup> Nevertheless, investigating how changes to the environment are perceived and  
17  
18 96 acted upon could provide greater understanding of how interventions work and thereby  
19  
20  
21 97 inform the design and targeting of future interventions.<sup>[13,15]</sup>  
22  
23  
24

98

### 99 **The iConnect study**

100 Connect2 is a programme of projects to promote walking and cycling at 79 sites around the  
101 UK. Each comprises a core engineering project such as a bridge over a busy road, railway or  
102 river, which together with the development or improvement of feeder routes was intended to  
103 make it easier for pedestrians and cyclists to reach destinations in their local area  
104 ([www.lotterygoodcauses.org.uk/project/sustrans-connect2](http://www.lotterygoodcauses.org.uk/project/sustrans-connect2)). The iConnect study began with  
105 the development of a general theoretical framework and a preliminary intervention model that  
106 was used to guide data collection and analysis.<sup>[16]</sup> Briefly, the model postulated that a  
107 Connect2 project may alter the physical accessibility of local destinations and other  
108 potentially relevant characteristics of the environment. It was always intended that this  
109 preliminary intervention model would be tested and refined in longitudinal analysis.<sup>[16]</sup> The  
110 main outcome evaluation has shown positive effects of the intervention on walking, cycling  
111 and overall physical activity after two years,<sup>[17]</sup> and qualitative interviews have highlighted  
112 the potential importance of visibility of the new infrastructure in fostering behaviour change  
113 in local people.<sup>[18]</sup> In this paper, we build on these findings by investigating the

1  
2  
3 114 'environmental' mechanisms linking the intervention with behaviour change. We did not set  
4  
5 115 out to test all the potential causal mechanisms for behaviour change in this context, such as  
6  
7 116 those involving psychological constructs such as confidence, intention or self-efficacy.  
8  
9 117 Instead we have focused on that part of the causal pathway most proximally related to the  
10  
11 118 intervention, which relates to perceptions of changes in the supportiveness of the  
12  
13 119 environment for walking and cycling, such as the convenience and safety of routes, and use  
14  
15 120 of the new infrastructure. We systematically describe and test a series of hypothesised  
16  
17 121 mediating processes, seeking to identify not only which mediators are important but also their  
18  
19 122 most plausible causal ordering. We then use the findings to refine the overall intervention  
20  
21 123 model and subsequently to assess the relative contributions of the different pathways to  
22  
23 124 behaviour change.  
24  
25  
26  
27  
28

## 29 126 **METHODS**

### 30 127 31 32 33 128 **Intervention, settings and data collection procedures**

34  
35 129 A more detailed description of the intervention, settings and data collection procedures is  
36  
37 130 available elsewhere.<sup>[19]</sup> Briefly, three Connect2 projects in Cardiff, Kenilworth  
38  
39 131 (Warwickshire) and Southampton were purposively selected as case study sites according to  
40  
41 132 criteria including implementation timetable, likelihood of measurable population impact, and  
42  
43 133 heterogeneity of overall mix of sites, including the composition of the local population and  
44  
45 134 the topographical context.<sup>[16, 18, 19]</sup> In Cardiff, pedestrians and cyclists travelling between the  
46  
47 135 city centre and the suburbs across Cardiff Bay had to share space with motor vehicles on a  
48  
49 136 busy road, and the centrepiece of the Connect2 project was a new 140m long, 4m wide  
50  
51 137 traffic-free bridge with integral lighting. In Kenilworth a new traffic-free bridge was built  
52  
53 138 across a busy trunk road to link the town to a rural greenway, and in Southampton a new  
54  
55  
56  
57  
58  
59  
60



1  
2  
3 139 400m boardwalk was built along the shore of the tidal River Itchen, replacing an informal  
4  
5 140 footpath which was impassable at high tide. Each project included improvements to feeder  
6  
7 141 routes which linked the new infrastructure with existing route networks.  
8  
9

10 142

11  
12 143 Questionnaires were posted to 22,500 adults aged 18 and over who were listed on the edited  
13  
14 144 electoral register as living within 5km by road of the core Connect2 project at any of the three  
15  
16 145 sites in April 2010. Information on demographic and socio-economic characteristics, travel  
17  
18 146 and physical activity behaviours, and perceptions of the environment were collected, and  
19  
20 147 additional questions were asked at follow-up to assess use of the Connect2 project. The  
21  
22 148 questionnaire is published in full elsewhere.<sup>[19]</sup> 3516 individuals returned questionnaires at  
23  
24 149 baseline, of whom 1510 (43%) also returned questionnaires at two-year follow-up in April  
25  
26 150 2012 after the opening of the new infrastructure. The University of Southampton Research  
27  
28 151 Ethics Committee granted ethical approval (CEE200809-15) and all participants provided  
29  
30 152 written informed consent.  
31  
32

33 153

### 34 154 **Measures**

35  
36  
37 155 As the main outcome evaluation showed that residential proximity to the new routes  
38  
39 156 predicted increases in weekly time spent walking and cycling (the primary outcome),<sup>[17]</sup> we  
40  
41 157 used the same measures of intervention exposure and outcome in this analysis.  
42  
43  
44

45 158

### 46 159 *Exposure*

47  
48  
49 160 Those living closer to the Connect2 projects were deemed to be more highly exposed to the  
50  
51 161 intervention than those living further away. Proximity to Connect2 was assessed using the  
52  
53 162 shortest distance between each participant's home address and the nearest access point to the  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 163 Connect2 project (including feeder routes) using an enhanced road network which included  
4  
5 164 traffic-free and informal paths.<sup>[19]</sup>  
6  
7  
8

9 165

10 166 *Outcome*

11 167 Walking and cycling for transport were assessed using a seven-day recall instrument covering  
12  
13 168 journeys made for five purposes: for commuting, on business, for study, for shopping and  
14  
15 169 personal business, and for social activities.<sup>[19]</sup> Participants reported the total time spent  
16  
17 170 walking and cycling for travel for each purpose, and these were summed across all purposes  
18  
19 171 for each mode of travel. Recreational physical activity was measured using an adapted  
20  
21 172 version of the short form of the International Physical Activity Questionnaire in which  
22  
23 173 participants reported the total time spent walking for recreation and cycling for recreation in  
24  
25 174 the past week.<sup>[20]</sup> Total weekly time spent walking and cycling was derived by summing the  
26  
27 175 times spent walking and cycling for transport and for recreation, and change scores were  
28  
29 176 computed as the time reported at follow-up minus the time reported at baseline.  
30  
31  
32  
33

34 177

35  
36 178 *Mediators*

37  
38 179 We hypothesised that the effects of Connect2 on overall walking and cycling might come  
39  
40 180 about as a result of participants' awareness of improvements in the physical and social  
41  
42 181 environmental conditions for those behaviours and their use of the new routes, which we  
43  
44 182 investigated as potential environmental mediators. At both time points, participants were  
45  
46 183 asked to report their agreement with seven items referring specifically to the physical  
47  
48 184 environment traversed by the Connect2 project, using a five-point Likert scale from strongly  
49  
50 185 disagree (-2) to strongly agree (+2) (Table 1). Four additional items asked about the visibility  
51  
52 186 of walking for travel, walking for recreation, cycling for travel and cycling for recreation in  
53  
54 187 terms of whether participants saw people engaging in these behaviours 'in my  
55  
56  
57  
58  
59  
60

1  
2  
3 188 neighbourhood'. Change scores for each of the physical environmental items were computed  
4  
5 189 as the difference between the baseline and follow-up measures, while change in the visibility  
6  
7 190 of walking and cycling was summarised using the mean of the corresponding change scores  
8  
9  
10 191 for the four individual items to match the outcome of total weekly time spent walking and  
11  
12 192 cycling. At follow-up, participants were also asked if they had walked or cycled on the  
13  
14 193 Connect2 project (yes/no).

15  
16  
17 194

18  
19 195 *Covariates*

20  
21 196 All demographic (sex, age, ethnicity and presence of any child under 16 in the household),  
22  
23 197 socioeconomic (highest educational level, annual household income and employment status)  
24  
25 198 and health variables (height, weight, general health, and presence of long-term illness or  
26  
27 199 disability limiting daily activities) were self-reported at baseline. Height and weight were  
28  
29  
30 200 used to compute Body Mass Index and assign participants to one of three categories of  
31  
32 201 weight status based on internationally recognised cut-offs.<sup>[21]</sup>

33  
34 202  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

203 **Table 1:** Items assessing (changes in) the perceived physical and social environment and rotated factor loadings  
204

Description	Item	Factor 1 'Change in infrastructure'	Factor 2 'Change in safety'
<b>Perceived physical environment</b>			
Safety for walking	Walking is unsafe because of the traffic	0.276	<b>0.809</b>
Safety for cycling	Cycling is unsafe because of the traffic	0.243	<b>0.804</b>
Pavements for walking	There are pavements suitable for walking	<b>0.732</b>	0.221
Special lanes for cycling	There are special lanes, routes or paths for cycling	<b>0.688</b>	0.280
Pleasant	The routes are pleasant for walking or cycling	<b>0.706</b>	0.203
Low crime	The level of crime or anti-social behaviour means walking or cycling is unsafe	-0.128	<b>0.678</b>
Lighting	The routes for walking and cycling are generally well lit at night	<b>0.695</b>	0.032
<b>Perceived social environment</b>			
Visibility of cycling for transport	I see people in my neighbourhood cycling for travel	n/a	n/a
Visibility of walking for transport	I see people in my neighbourhood walking for travel	n/a	n/a
Visibility of cycling for recreation	I see people in my neighbourhood cycling for recreation	n/a	n/a
Visibility of walking for recreation	I see people in my neighbourhood walking for recreation	n/a	n/a

205  
206 n/a: not applicable as this variable was not used in factor analysis. Factor analysis was based on 1211 participants for whom change scores for all  
207 relevant items were available.  
208

209

**Analysis**

Our analysis was divided into three steps. We first explored the factor structure of the items assessing perceptions of the physical environment, to identify whether groups of items were related and changed in similar ways (step 1: see below). This reflected the fact that the Connect2 projects aimed to improve the environment for walking and cycling more generally, rather than targeting single aspects such as safety or pleasantness. We then identified candidate mediators and their most plausible conceptual ordering by systematically exploring the associations between the environmental perception measures (factor scores for the physical environmental items, and the mean change score for the visibility items), proximity to and use of Connect2, and change in time spent walking and cycling (step 2). Having thereby refined our intervention theory, we then used path analysis — a confirmatory analysis technique — to formally test the model and estimate the magnitude and significance of the hypothesised causal relationships between the sets of variables (step 3).<sup>[22]</sup> All analyses were restricted to participants who had not moved home during the study and whose total reported physical activity had not changed by >900 min/week, which may have come about as a result of misreporting (e.g. misreporting 15 minutes as 15 hours). Steps 1 and 2 were conducted using STATA, and step 3 using Mplus.

226

*Step 1: Factor analysis of changes in perceptions of the physical environment*

A principal components analysis was conducted on the items assessing perceptions of the physical environment at baseline and at follow-up, as well as on the change scores. Factors with an eigenvalue less than one were dropped, factor loadings were rotated using varimax (orthogonal) rotation and factors were scored by the method suggested by Bartlett,<sup>[23]</sup> creating scores for each factor weighted according to the item loadings.<sup>[24]</sup> These analyses were further restricted to participants who had completed all the physical environmental perception items at both time points.

235

236 *Step 2: Identification of mediators and refinement of intervention theory*

237 We systematically tested the associations (i) between proximity to Connect2 and the hypothesised  
238 mediators (changes in the environmental perception measures and use of Connect2); (ii) between  
239 these hypothesised mediators and change in walking and cycling; and (iii) between the various  
240 mediators. We fitted separate linear or logistic regression models as appropriate for all the  
241 associations tested. These were adjusted for total weekly time spent walking and cycling at  
242 baseline and all the demographic, socioeconomic and health characteristics listed above, but were  
243 not adjusted for the other mediators. The objective was not to isolate statistically significant single  
244 associations, but to identify plausible links in a causal pathway to be carried forward to the next  
245 stage of analysis, as advocated by Victora and colleagues.<sup>[13]</sup> We therefore applied a generous  
246 criterion of  $p < 0.25$  to identify 'plausible' associations at this stage. However, because the aim of  
247 the analysis was to elucidate mechanisms for an *intervention* that had already been shown to be  
248 positively associated with the behaviour change outcomes, we carried forward only those  
249 mediators that were directly associated with both the exposure and either the outcome or another  
250 mediator, and for which all the observed associations were in the expected (i.e. positive) direction.

251

252 *Step 3: Testing the intervention model*

253 The resulting model was tested using path analysis, in other words using a structural equation  
254 model with no latent variables. This approach allows sets of relationships between variables to be  
255 modelled simultaneously, using linear or logistic regression as appropriate according to the form  
256 of the dependent variables and with the mediating variables being treated as both dependent and  
257 independent variables.<sup>[25]</sup> It is a confirmatory form of analysis in which a model depicting  
258 unidirectional causal effects of one variable on another is tested with no possibility of  
259 incorporating feedback loops.<sup>[26]</sup> We adopted a complete case approach, restricting these analyses

1  
2 260 to participants who had provided data on exposure, outcome and all mediators and covariates, and  
3  
4 261 used maximum likelihood estimation with 1000 iterations.  
5  
6  
7 262

### 8 263 *Stratified analyses*

10 264 We further hypothesised that different mechanisms of behaviour change might have operated in  
11  
12  
13 265 people with different levels of walking and cycling prior to the intervention. We therefore divided  
14  
15 266 the sample at the median total time spent walking and cycling at baseline (190 min/week) and  
16  
17 267 repeated steps 2 and 3 in the low-active and high-active subgroups. Because there remained  
18  
19 268 significant variation in baseline activity within each subgroup, we also adjusted for time spent  
20  
21 269 walking and cycling at baseline in these models.  
22  
23  
24 270

## 26 271 **RESULTS**

### 28 272

### 30 273 **Sample characteristics**

32 274 Of the 1510 participants who returned survey data at baseline and follow-up, 1465 met the  
33  
34 275 inclusion criteria for the main outcome evaluation (had neither moved home nor reported a large  
35  
36 276 change in physical activity) and 1211 provided information sufficient for the factor analysis in step  
37  
38 277 1 in this analysis. The sample size for each regression model in step 2 ranged from 969 to 1139  
39  
40 278 according to the completeness of reporting of the various mediators. 967 participants provided  
41  
42 279 complete data on exposure, outcome, and all mediators and covariates, and comprised the sample  
43  
44 280 for the analysis in step 3. Compared to the sample of 1465 used for the main outcome  
45  
46 281 evaluation,<sup>[17]</sup> our final subsample was slightly younger on average and included a higher  
47  
48 282 proportion of men (Table 2). Participants in this final subsample were also more likely to be  
49  
50 283 educated to tertiary level, to have access to a car and to a bicycle and to have a child in their  
51  
52 284 household, and less likely to report having a long term health condition (all  $p < 0.001$ ). However,  
53  
54  
55  
56  
57  
58  
59  
60

1  
2 285 our subsample was not significantly different from the main sample in terms of ethnicity, weight  
3  
4 286 status or time spent walking and cycling at baseline.  
5  
6 287  
7  
8 288  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

For peer review only



289 **Table 2:** Characteristics of the sample

290

Variable	Category	Participants providing data on exposure and outcome (n=1465) % (N)	Participants providing data on exposure, outcome and all mediators and covariates (n=967) % (N)
Site	Cardiff	32.3 (473)	33.6 (325)
	Kenilworth	39.9 (584)	40.7 (394)
	Southampton	27.9 (408)	25.7 (248)
Residential proximity to intervention (km)	≥4	9.6 (141)	9.7 (93)
	3-3.99	7.0 (103)	6.9 (66)
	2-2.99	15.2 (222)	15.2 (147)
	1-1.99	32.4 (474)	31.6 (306)
	<1	35.8 (525)	36.6 (355)
Sex	Female	56.7 (831)	51.9 (502)
	Male	43.3 (634)	48.1 (465)
Age (years) at baseline	18-34	9.7 (141)	11.0 (107)
	35-49	19.9 (291)	24.1 (233)
	50-64	35.5 (519)	38.5 (372)
	65-89	34.9 (510)	26.4 (255)
Ethnicity	White	96.9 (1417)	97.2 (940)
	Non-White	3.1 (45)	2.8 (27)
Any child under 16 in household	No	84.4 (1236)	81.1 (784)
	Yes	15.6 (229)	18.9 (183)
Highest educational level	Tertiary or higher	39.5 (576)	45.9 (444)
	Secondary school	32.8 (479)	32.9 (318)
	Lower than secondary	27.7 (405)	21.2 (205)
Annual household Income	>£40,000	32.1 (439)	36.6 (355)
	£20,001-40,000	33.7 (461)	35.0 (337)
	≤£20,000	34.3 (469)	28.4 (275)
Employment Status	Working	49.2 (720)	56.7 (548)
	Student	1.6 (24)	1.4 (14)
	Retired	40.3 (589)	33.2 (321)
	Other	8.9 (130)	8.7 (84)
Any car in household	No	13.9 (203)	10.0 (97)
	Yes	86.1 (125)	90.0 (870)
Any adult bicycle in household	No	44.6 (603)	39.5 (382)
	Yes	55.4 (748)	60.5 (585)
Weight status	Normal/underweight	49.0 (683)	48.4 (468)
	Overweight	37.0 (515)	37.6 (363)
	Obese	14.0 (195)	14.0 (136)
General health	Excellent/good	78.5 (113)	81.6 (789)
	Fair/poor	21.5 (312)	18.4 (178)
Long-term illness or disability that limits daily activities	No	74.0 (102)	78.1 (756)
	Yes	26.0 (359)	21.9 (211)
Time spent walking and	None	15.6 (229)	14.0 (135)

Variable	Category	Participants providing data on exposure and outcome (n=1465)  % (N)	Participants providing data on exposure, outcome and all mediators and covariates (n=967)  % (N)
cycling in past week (min)	1-149	25.7 (376)	27.2 (263)
	150-299	23.5 (344)	23.6 (229)
	300-449	14.4 (211)	14.2 (138)
	≥450	20.8 (305)	20.9 (202)

291

292

293

For peer review only

1  
2 294 **Step 1: Factor analysis of changes in perceptions of the physical environment**

3  
4 295 The results of the factor analyses of the baseline and follow-up values were similar to those of the  
5  
6 296 factor analysis of the change scores (Additional File 1). We therefore chose to use the factors and  
7  
8  
9 297 factor scores derived from the change scores. We identified two meaningful factors, which we  
10  
11 298 described as representing perceived changes in infrastructure (eigenvalue: 2.9) and perceived  
12  
13 299 changes in safety (eigenvalue: 1.2) (Table 1). These factors explained 58% of the variance in the  
14  
15 300 change scores for the physical environmental perception items.  
16  
17  
18 301

19  
20 302 **Step 2: Identification of mediators and refinement of intervention theory**

21  
22 303

23  
24 304 *Whole sample*

25  
26 305 Table 3 summarises the associations between the putative mediators, proximity to Connect2 and  
27  
28 306 change in time spent walking and cycling. As reported elsewhere,<sup>[17,27]</sup> proximity to Connect2 was  
29  
30 307 associated with use (OR=1.85,  $p<0.001$ ; Table 3a) and use of Connect2 was associated with  
31  
32 308 change in time spent walking and cycling ( $\beta=31.16$ ,  $p=0.06$ ; Table 3b). Proximity to Connect2 was  
33  
34 309 associated with perceived changes in infrastructure and visibility (both  $\beta=0.05$ ,  $p\leq 0.03$ ) and safety  
35  
36 310 ( $\beta=0.03$ ,  $p=0.18$ ; Table 3c). Although all of these also met the criteria for a plausible association  
37  
38 311 with use of Connect2 ( $1.23\leq OR\leq 1.33$ , all  $p\leq 0.008$ ; Table 3d), only a perceived change in safety  
39  
40 312 was directly associated with change in time spent walking and cycling ( $\beta=9.19$ ,  $p=0.22$ ; Table 3e).  
41  
42 313 The association between perceived changes in infrastructure and visibility also met the criteria for  
43  
44 314 inclusion ( $\beta=0.06$ ,  $p=0.04$ ), while those between perceived changes in safety and infrastructure or  
45  
46 315 visibility did not (Table 3f).  
47  
48  
49  
50

51 316  
52  
53  
54  
55  
56  
57  
58  
59  
60

317 **Table 3:** Associations between potential mediators, proximity to intervention and change in  
 318 walking and cycling  
 319

<b>(a) Associations between proximity to and use of intervention</b>		
<b>Independent variable: Residential proximity to intervention (km)</b>		
<b>Dependent variable</b>	<b>OR (95% CI)</b>	<b>p</b>
Use of intervention (yes/no)	1.85 (1.61, 2.11)	0.001
<b>(b) Associations between use of intervention and change in walking and cycling</b>		
<b>Independent variable: Use of intervention (yes/no)</b>		
<b>Dependent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in time spent walking and cycling (min/week)	31.16 (-1.72, 64.05)	0.063
<b>(c) Associations between proximity to intervention and perceived environmental changes</b>		
<b>Independent variable: Residential proximity to intervention (km)</b>		
<b>Dependent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	0.05 (0.01, 0.10)	0.030
Change in safety	0.03 (-0.02, 0.08)	0.182
Change in visibility	0.05 (0.01, 0.10)	0.013
<b>(d) Associations between perceived environmental changes and use of intervention</b>		
<b>Dependent variable: Use of intervention (yes/no)</b>		
<b>Independent variable</b>	<b>OR (95% CI)</b>	<b>p</b>
Change in infrastructure	1.23 (1.06, 1.44)	0.008
Change in safety	1.31 (1.13, 1.54)	0.001
Change in visibility	1.33 (1.15, 1.55)	0.001
<b>(e) Associations between perceived environmental changes and change in walking and cycling</b>		
<b>Dependent variable: Change in time spent walking and cycling (min/week)</b>		
<b>Independent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	-2.51 (-17.16, 12.13)	0.736
Change in safety	9.19 (-5.36, 23.74)	0.215
Change in visibility	-6.21 (-20.62, 8.19)	0.398
<b>(f) Associations between perceived environmental changes</b>		
<b>Dependent variable: Change in visibility</b>		
<b>Independent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	0.06 (0.00, 0.12)	0.039
Change in safety	0.03 (-0.03, 0.09)	0.328
<b>Dependent variable: Change in safety</b>		
<b>Independent variable</b>		
Change in infrastructure	-0.03 (-0.10, 0.03)	0.215

320  
 321 Linear or logistic regression models as appropriate adjusted for time spent walking and cycling at  
 322 baseline and the demographic, socioeconomic and health characteristics shown in Table 2.  
 323 Proximity was modelled as the negative of the distance between home and the nearest access point  
 324 to the 'greater Connect2 project' including feeder routes. Each row represents a separate model  
 325 which was not adjusted for the other mediators.  
 326  
 327

1  
2 328 Based on these results, a path model was developed to capture the most plausible theory of change  
3  
4 329 linking proximity to the intervention with change in time spent walking and cycling (Figure 1a).  
5  
6 330 Perceived changes in infrastructure, safety and visibility were all associated with proximity, and  
7  
8 331 because these were hypothesised to change as a direct and proximate result of the intervention they  
9  
10 332 were placed directly after proximity in the model. All three perceived changes were also associated  
11  
12 333 with use of the intervention, and we assumed that the more plausible causal ordering was that the  
13  
14 334 changes in the perceived supportiveness of the environment may have led to use of the new  
15  
16 335 infrastructure. Use was also associated with proximity and with change in time spent walking and  
17  
18 336 cycling, so we included an additional indirect path between exposure and outcome via use only.  
19  
20 337 Only one of the interrelationships between the perceived environmental changes – that between  
21  
22 338 infrastructure and visibility – was identified as plausible, and we assumed that perceived  
23  
24 339 improvements in infrastructure were more likely to reflect a direct and proximate effect of the  
25  
26 340 *physical* intervention and may therefore have preceded the perceived change in the visibility of  
27  
28 341 walking and cycling. Given the lack of clear theory or evidence in relation to the causal ordering  
29  
30 342 of some of these mediators, however, we developed two alternative models that were also  
31  
32 343 consistent with the associations observed in step 2: one in which the perceived change in visibility  
33  
34 344 preceded the perceived change in infrastructure (Alternative 1), and one in which the perceived  
35  
36 345 change in safety followed use of the infrastructure (Alternative 2; Additional File 2).  
37  
38  
39  
40  
41  
42  
43

346

347 *Low-active subgroup*

348 In the low-active subgroup, proximity to Connect2 was associated with use (OR=2.05, p=0.001)  
349 and use of the infrastructure was associated with change in time spent walking and cycling  
350 ( $\beta=62.96$ ,  $p<0.001$ ; Additional File 3a, 3b). Proximity was associated with perceived changes in  
351 safety ( $\beta=0.08$ ,  $p=0.03$ ) and infrastructure ( $\beta=0.05$ ,  $p=0.15$ ), but the association with change in  
352 visibility did not meet the criteria for inclusion (Additional File 3c). Perceived changes in safety  
353 and visibility, but not in infrastructure, met the criteria for a plausible association with use of

1  
2 354 Connect2 ( $1.14 \leq OR \leq 1.42$ ,  $p < 0.25$ ; Additional File 3d). None of the associations between the  
3  
4 355 putative mediators and change in time spent walking and cycling met the criteria for inclusion, nor  
5  
6 356 did those between the various perceived environmental changes (Additional File 3e, 3f). While  
7  
8 357 perceived changes in infrastructure and visibility therefore met the criteria for inclusion in the  
9  
10 358 model based on single associations (with proximity and use respectively), they could not be linked  
11  
12 359 on a pathway and were therefore deemed not to be plausibly causally related to the effects of the  
13  
14 360 intervention in this subsample. Perceived change in safety, and use of the infrastructure, were  
15  
16 361 therefore the only mediators included in the model for this subgroup (Figure 1b).  
17  
18  
19  
20 362

### 21 363 *High-active subgroup*

22 364 Similarly, in the high-active subgroup proximity to Connect2 was associated with use of the  
23  
24 365 infrastructure ( $OR = 1.79$ ,  $p = 0.001$ ) and use was associated with change in time spent walking and  
25  
26 366 cycling ( $\beta = 83.97$ ,  $p < 0.001$ ) (Additional File 4a, 4b). Proximity was associated with perceived  
27  
28 367 changes in visibility and infrastructure ( $0.06 \leq \beta \leq 0.10$ , both  $p < 0.08$ ), but the association with  
29  
30 368 perceived change in safety did not meet the criteria for inclusion (Additional File 4c). All three  
31  
32 369 perceived environmental changes met the criteria for a plausible direct association with use of  
33  
34 370 Connect2 ( $1.21 \leq OR \leq 1.58$ ,  $p < 0.09$ ), but not with change in time spent walking and cycling  
35  
36 371 (Additional File 4d, 4e). The association between perceived changes in infrastructure and visibility  
37  
38 372 also met the criteria for inclusion ( $\beta = 0.11$ ,  $p = 0.02$ ; Additional File 4f). Based on these results, we  
39  
40 373 developed the path model shown in Figure 1c.  
41  
42  
43  
44  
45  
46 374

### 47 375 **Step 3: Testing the intervention model**

48  
49 376 The model shown in Figure 1a was fitted in path analysis for the whole sample (Table 4). The  
50  
51 377 effect of proximity to the intervention on change in time spent walking and cycling was almost  
52  
53 378 entirely explained by an indirect path via use of the infrastructure (path 2, 90%), while the  
54  
55 379 remaining indirect paths that included perceived changes in infrastructure, safety or visibility  
56  
57  
58  
59  
60

380 together explained only 8% of the effect. Path analysis of the alternative models incorporating  
 381 different causal ordering of the mediators gave very similar results (Additional File 2), as did path  
 382 analysis of the models for the low- and high-active subgroups (Additional File 5).

383

384 **Table 4:** Contributions of different pathways to behaviour change

385

Path	$\beta$ (95% CI)	% of effect explained
Indirect via safety only (path 1)	0.21 (-0.68, 1.09)	0.4
Indirect via use only (path 2)	43.13 (22.09,	89.9
Indirect via infrastructure and use (path 3)	1.33 (0.03, 2.63)	2.8
Indirect via safety and use (path 4)	1.38 (-0.04, 2.81)	2.9
Indirect via visibility and use (path 5)	0.76 (-0.14, 1.65)	1.6
Indirect via infrastructure, visibility and use (path 6)	0.09 (-0.03, 0.20)	0.2
Direct (path 7)	1.09 (-9.63, 11.81)	2.2
Total (sum of paths 1-7)	47.99 (26.32,	100

386

387

388 Model shown in Figure 1 (a) fitted using path analysis in Mplus, adjusted for time spent walking  
 389 and cycling at baseline and the demographic, socioeconomic and health characteristics shown in  
 390 Table 2.

391

## 392 DISCUSSION

393

### 394 Principal findings

395 In this study we have refined and tested key components of a theoretical model linking the  
 396 provision of new walking and cycling routes with changes in walking and cycling behaviour in  
 397 local communities. In doing so, we have made both methodological and substantive contributions  
 398 to the challenge of evaluating and understanding the effects of interventions to change the  
 399 environmental determinants of health, which are understood to work through long and potentially  
 400 complex causal pathways.<sup>[13]</sup> Having previously developed a provisional intervention model, we  
 401 systematically identified the most plausible mediators, associations and causal ordering, refined  
 402 the model, and then formally tested the model using path analysis. We found that exposure to the  
 403 intervention was associated with changes in the perceived supportiveness of the physical and

1  
2 404 social environments for walking and cycling, even after adjustment for baseline levels of those  
3  
4 405 behaviours and other potential confounders. This suggests that the intervention was at least  
5  
6 406 somewhat successful in changing those aspects of the environment. However, path analysis  
7  
8 407 showed that the effects of the intervention on changes in walking and cycling were largely  
9  
10 408 explained only by use of the new infrastructure, and that other explanatory pathways involving  
11  
12 409 changes in cognitions relating to the environment explained only a small proportion of the effect.  
13  
14 410 This overall finding was replicated in separate analyses restricted to participants with lower or  
15  
16 411 higher levels of activity at baseline, although there were differences in the specific patterns of  
17  
18 412 associations observed.  
19  
20  
21  
22 413

#### 23 24 414 **Strengths and limitations**

25  
26 415 In the context of an intervention to change environmental determinants of health, we have  
27  
28 416 systematically identified the most important environmental mediators and their most plausible  
29  
30 417 causal ordering, and tested and compared a series of mediating pathways, in order to improve our  
31  
32 418 theory of how such interventions may work. Our study was conducted as a natural experiment  
33  
34 419 using general population samples drawn from three contrasting communities, which confers a  
35  
36 420 degree of external validity that may be lacking from some behavioural research conducted in less  
37  
38 421 natural settings. A further strength lies in the specificity of the measures of perceptions of the  
39  
40 422 physical environment, which were both specific to the area traversed by the intervention and  
41  
42 423 hypothesised to change as a direct result of the intervention. Our approach to analysis was  
43  
44 424 underpinned by a specific preliminary theoretical model for the intervention<sup>[19]</sup> and the pathways  
45  
46 425 tested were consistent with the principles outlined in more general behavioural frameworks such as  
47  
48 426 EnRG.<sup>[28]</sup> While the testing and refinement of theory in this way is commonly applied in the  
49  
50 427 analysis of qualitative data,<sup>[29]</sup> it is less commonly (or explicitly) applied in the statistical analysis  
51  
52 428 of quantitative data in public health research. This study therefore offers a methodological  
53  
54 429 contribution to the challenge of evaluating and understanding complex public health interventions,  
55  
56  
57  
58  
59  
60



1  
2 430 an area in which both the theory of behaviour change and the methods for evaluation remain  
3  
4 431 under-developed.<sup>[29]</sup> Partly for this reason, we used generous statistical criteria to identifying  
5  
6 432 plausible pathways for further testing and we also tested some alternative model configurations,  
7  
8 433 which showed that our assumptions about the causal ordering of mediators made little difference  
9  
10 434 to the relative importance of the main pathways identified. We have tried to document our  
11  
12 435 methods as clearly as possible in the hope that other researchers will adapt and refine our methods,  
13  
14 436 investigate the replicability of our findings in other populations and settings, and explore the wider  
15  
16 437 applicability of this approach in public health research.  
17  
18  
19  
20 438

21  
22 439 Nevertheless, this study had several important limitations. First, we restricted our analysis to  
23  
24 440 participants with complete data on all mediators, which produced a sample for analysis that was  
25  
26 441 somewhat younger and healthier than the main study sample.<sup>[17]</sup> This, together with the low initial  
27  
28 442 response rate, means that our sample cannot be assumed to be representative of the local resident  
29  
30 443 populations. Second, although our measures of perceptions of the physical environment were  
31  
32 444 highly specific, we used more composite measures of perceptions of the social environment and of  
33  
34 445 the behavioural outcomes, to ensure comparability with the main outcome evaluation and because  
35  
36 446 the largest intervention effect was observed for the composite outcome of overall time spent  
37  
38 447 walking and cycling.<sup>[17]</sup> We acknowledge the need for further investigation of more specific  
39  
40 448 exposure-outcome relationships which may shed more light on how changes in specific  
41  
42 449 behavioural outcomes come about.<sup>[30]</sup> Third, because changes in putative mediators and changes in  
43  
44 450 behaviour were assessed over the same time period, we cannot be certain if changes in mediators  
45  
46 451 led to changes in physical activity or vice versa. On the other hand, whereas most existing research  
47  
48 452 on the mediators of the relationship between physical activity and the environment has explored  
49  
50 453 only cross-sectional associations, which provide little basis for causal inference,<sup>[31-33]</sup> a key  
51  
52 454 strength of our analysis is that it used longitudinal data from an intervention study in which  
53  
54  
55  
56  
57  
58  
59  
60

1  
2 455 environmental changes were known to have been introduced and could reasonably be assumed to  
3  
4 456 have causally preceded the changes observed.<sup>[11]</sup>  
5  
6  
7 457

#### 8 458 **Understanding intervention mechanisms to strengthen the basis for causal inference**

9  
10 459 Our investigation not only provides greater understanding of the causal explanation of how  
11  
12 460 behaviour change comes about as a consequence of an environmental intervention, but also  
13  
14 461 provides a stronger basis for causal attribution. This was a natural experimental study in which  
15  
16 462 participants were not randomised to allocation status, but were exposed to the intervention to a  
17  
18 463 greater or lesser extent according to the proximity of their home to the new infrastructure. In  
19  
20 464 studies of this kind we can never be entirely sure that the analysis of the main effect is free from  
21  
22 465 residual confounding by unobserved variables, which can neither be controlled for in analysis nor  
23  
24 466 assumed to be balanced between groups as in a randomised controlled trial.<sup>[34,35]</sup> However, we  
25  
26 467 have demonstrated a plausible, logical and parsimonious pathway linking geographical exposure to  
27  
28 468 the intervention via individual use of the intervention to individual changes in walking and cycling  
29  
30 469 behaviour, and we have shown that this mechanism explains the large majority of the effect of the  
31  
32 470 intervention. This evidence for *how* an intervention achieves its effects (*causal explanation*) can be  
33  
34 471 combined with the evidence for the size of those effects (*causal estimation*) reported elsewhere<sup>[17]</sup>  
35  
36 472 to provide a stronger basis for valid causal inference.<sup>[13]</sup>  
37  
38  
39  
40  
41  
42  
43

#### 44 474 **Identifying modifiable perceptions of the physical and social environment**

45  
46 475 The rationale for selecting intervention sites for the Connect2 programme was to improve  
47  
48 476 provision for local walking and cycling journeys in places where existing provision was poor. For  
49  
50 477 example, the project in Cardiff involved providing a new traffic-free river crossing as an  
51  
52 478 alternative to sharing space with motor vehicles on a busy road bridge or making a long detour,<sup>[19]</sup>  
53  
54 479 factors which qualitative research with local informants identified as barriers to walking or  
55  
56 480 cycling.<sup>[18]</sup> In our analysis, proximity to and use of the intervention both showed significant  
57  
58  
59  
60

1  
2 481 associations with perceived changes in infrastructure and safety for walking and cycling and with  
3  
4 482 the perceived visibility of those behaviours in the neighbourhood. This provides some evidence  
5  
6 483 that the Connect2 programme was successful in influencing these characteristics of the  
7  
8 484 environment, and that these changes may have contributed to people taking up the opportunity to  
9  
10 485 use the new infrastructure. Restricting the analysis to participants with a higher level of activity at  
11  
12 486 baseline revealed a similar pattern of associations to that observed in the whole sample, whereas in  
13  
14 487 the low-active subgroup a perceived change in safety was the only environmental mediator found  
15  
16 488 to be associated with both exposure and use. Consistent with findings from some cross-sectional  
17  
18 489 and longitudinal studies,<sup>[36]</sup> this suggests that improving safety – reflected in this study by survey  
19  
20 490 questions about safety from crime or antisocial behaviour, as well as safety from traffic – may be  
21  
22 491 particularly important in promoting the use of walking and cycling routes among those with the  
23  
24 492 most capacity to benefit from an increase in physical activity.  
25  
26  
27  
28  
29

493

#### 494 **The role of behaviour-specific cognitions in behaviour change**

32  
33 495 Despite the fact that perceived changes in the physical and social environment were reported by  
34  
35 496 people living in the areas served by the Connect2 projects and associated with use of the new  
36  
37 497 routes, we found that pathways between intervention exposure and behaviour change involving  
38  
39 498 these perceived changes explained a very small percentage of the intervention effect, 90% of  
40  
41 499 which was accounted for by use of the intervention alone. This may appear a slightly unexpected  
42  
43 500 finding, given the body of cross-sectional evidence suggesting a relationship between physical  
44  
45 501 activity behaviours and the perceived supportiveness of the environment.<sup>[8,9]</sup>  
46  
47  
48

502

50 503 Perceived environmental changes were only weakly associated with changes in time spent walking  
51  
52 504 and cycling, suggesting that they played a relatively small part in determining overall behaviour  
53  
54 505 change in the sample. Importantly, the largest contributor to the increase in overall time spent  
55  
56 506 walking and cycling was an increase in recreational walking,<sup>[17]</sup> whereas at baseline perceptions of  
57  
58  
59  
60

1  
2 507 the environment were generally more strongly associated with walking or cycling for transport  
3  
4 508 than with walking or cycling for recreation.<sup>[37]</sup> The latter finding is consistent with existing  
5  
6 509 literature in which attributes of the environment have been found to have mixed patterns of  
7  
8 510 associations with walking and cycling, and with recreational and transport activities.<sup>[8,9]</sup> It is  
9  
10 511 therefore possible that stronger evidence of mediation might have been found for other  
11  
12 512 unmeasured environmental attributes more closely related to recreational activities (or indeed for  
13  
14 513 other psychological constructs such as confidence, intention or self-efficacy, which were not the  
15  
16 514 focus of this study).  
17  
18  
19  
20 515

21  
22 516 An alternative interpretation of the weak evidence for the mediating role of behaviour-specific  
23  
24 517 cognitions in this study is that it supports the notion of more automatic, unconscious processes  
25  
26 518 linking environmental change with behaviour change. Behavioural scientists have described how  
27  
28 519 behaviour may be determined by a more reflective, goal-orientated system on the one hand or by a  
29  
30 520 more automatic, affective system on the other,<sup>[38]</sup> and Kremers and colleagues have specifically  
31  
32 521 referred to both ‘mediated’ and ‘unmediated’ pathways in the context of the influence of the  
33  
34 522 environment on energy-related behaviours.<sup>[28]</sup> Our findings could be regarded as consistent with,  
35  
36 523 although certainly not proof of, the hypothesis that physical activity behaviour change can be  
37  
38 524 promoted by altering relevant environmental cues — sometimes referred to as changing choice  
39  
40 525 architecture<sup>[39]</sup> or ‘nudging’<sup>[40]</sup> — without explicitly encouraging the target behaviours or directly  
41  
42 526 addressing people’s perceptions and other cognitions relating to them.<sup>[41]</sup> Indeed, the fact that  
43  
44 527 behaviour change in this study was strongly associated with proximity to and use of the  
45  
46 528 infrastructure, but only weakly associated with people’s perceptions of how the environment had  
47  
48 529 changed, suggests that the physical improvement of the environment itself — rather than the  
49  
50 530 modification of people’s perceptions of their environment — was the key to the effectiveness of  
51  
52 531 the intervention.  
53  
54  
55  
56  
57 532

### 533 **Implications for future research**

534 As many authors have pointed out, few studies have evaluated the effects of environmental  
535 approaches to changing population physical activity behaviour, and even fewer have gone beyond  
536 estimating their effects to investigate the mechanisms underlying the (in)effectiveness of  
537 interventions.<sup>[5,10,11,42,43]</sup> Complementary evidence of effects and mechanisms will help strengthen  
538 the case for causal inference, particularly in a field in which randomised controlled trials are rarely  
539 feasible.<sup>[12,13]</sup> More work is required to refine the hypotheses about how specific interventions may  
540 work and to generate improved measures to reflect the proposed mechanisms. The former might  
541 include investigating the social (collective) mechanisms of behaviour change and their interaction  
542 with individual factors. For example, it is unknown whether the impact of environmental change is  
543 more or less important for those with different attitudes to physical activity, and some authors have  
544 suggested the existence of synergistic or competitive mechanisms.<sup>[44]</sup> The latter might include  
545 developing objective measures of the nature, extent, timing and quality of environmental  
546 change,<sup>[45]</sup> as well as detailed individual-level measures of the ‘dose’ of intervention received —  
547 such as exposure to and use of new environments— and of how interventions are received and  
548 interpreted. Improved measures of this kind will enable the hypothesised pathways to behaviour  
549 change to be tested — and preferably reported as transparently as possible, as recommended by the  
550 authors of a recent review<sup>[46]</sup> — in order to identify the most promising strategies for future  
551 interventions to change the environmental determinants of health.

552

### 553 **CONCLUSIONS**

554 Local residents’ perceptions of the supportiveness of the physical and social environment for  
555 walking and cycling were changed after the construction of new infrastructure in their  
556 communities. However, the effect of the intervention on overall walking and cycling was largely  
557 explained by a simple causal pathway involving use of the new routes, and other explanatory  
558 pathways involving changes in cognitions relating to the environment explained only a small

1  
2 559 proportion of the overall effect. These findings imply that cognitive processing of environmental  
3  
4 560 conditions may play a limited role in behaviour change, and that high-quality changes to the  
5  
6 561 physical environment itself — rather than changing people’s perceptions of their environment —  
7  
8 562 may be the key to the effectiveness of this type of intervention. Studies of how interventions lead  
9  
10 563 to behaviour change should complement those concerned with estimating their effects in  
11  
12 564 supporting valid causal inference in public health research.  
13  
14  
15  
16

17 565  
18 566 **Contributors:** JP and DO designed the analysis. JP analysed the data. Both interpreted the data,  
19  
20 567 drafted the article and revised it critically for important intellectual content, and approved the final  
21  
22 568 version of the submitted manuscript.  
23

24 569 **Acknowledgements:** This article was written on behalf of the iConnect consortium  
25  
26 570 (<http://www.iconnect.ac.uk>: Christian Brand, Fiona Bull, Ashley Cooper, Andy Day, Nanette  
27  
28 571 Mutrie, David Ogilvie, Jane Powell, John Preston, and Harry Rutter). The iConnect consortium is  
29  
30 572 funded by the Engineering and Physical Sciences Research Council (EPSRC) [grant  
31  
32 573 EP/G00059X/1], Jenna Panter is funded by a National Institute for Health Research (NIHR) Post-  
33  
34 574 Doctoral Fellowship [PDF 2012-05-157], and David Ogilvie is supported by the Medical Research  
35  
36 575 Council (MRC) [Unit programme number MC\_UU\_12015/6]. This article presents independent  
37  
38 576 research in which the funders had no involvement in the study design; the collection, analysis, and  
39  
40 577 interpretation of data; the writing of the article; or the decision to submit the article for publication.  
41  
42 578 The views expressed are those of the authors and not necessarily those of the NHS, the NIHR, the  
43  
44 579 Department of Health or the other funders. We thank the study participants for their cooperation  
45  
46  
47 580 and the study team led by Karen Ghali for managing data collection.  
48  
49  
50

51 581

52  
53 582 **Competing interests:** None.  
54  
55  
56 583

1  
2 584 **Data sharing:** The dataset used in this study is managed by the MRC Epidemiology Unit at the  
3  
4 585 University of Cambridge. The access policy for sharing is based on the MRC Policy and Guidance  
5  
6 586 on Sharing of Research Data from Population and Patient Studies. All data sharing must meet the  
7  
8 587 terms of existing participants' consent and study ethical approvals. Our Data Access and Sharing  
9  
10 588 Policy defines the principles and processes for accessing and sharing our data. We welcome  
11  
12 589 proposals for projects and aim to make data as widely available as possible whilst safeguarding the  
13  
14 590 privacy of our participants, protecting confidential data and maintaining the reputations of our  
15  
16 591 studies and participants. All data sharing is dependent on the project being approved by the study  
17  
18 592 team, a data sharing agreement being in place with the University of Cambridge and resources  
19  
20 593 being available to support the request. For further information please refer to the MRC  
21  
22 594 Epidemiology Unit data sharing portal at <http://epi-meta.medschl.cam.ac.uk>.  
23  
24  
25  
26  
27

595

596 **References**

597

- 598 1. Das P, Horton R. Rethinking our approach to physical activity. *Lancet* 2012;**380**(9838):189-90.
- 599 2. Saunders LE, Green JM, Petticrew MP, et al. What are the health benefits of active travel? A  
600 systematic review of trials and cohort studies. *PLoS One* 2013;**8**(8):e69912.
- 601 3. Appleyard D. *Livable Streets*. Berkeley California: University of California Press, 1982.
- 602 4. Woodcock J, Edwards P, Tonne C, et al. Public health benefits of strategies to reduce  
603 greenhouse-gas emissions: urban land transport. *Lancet* 2009;**374**(9705):1930-43.
- 604 5. Ogilvie D, Egan M, Hamilton V, et al. Promoting walking and cycling as an alternative to using  
605 cars: systematic review. *BMJ* 2004;**329**:763-66.
- 606 6. Ogilvie D, Foster C, Rothnie H, et al. Interventions to promote walking: systematic review.  
607 *BMJ* 2007;**334**:1204-07.
- 608 7. Yang L, McMinn A, Sahlqvist S, et al. Interventions to promote cycling: systematic review.  
609 *BMJ* 2010;**341**:c5293.
- 610 8. Saelens B, Sallis J, Frank L. Environmental correlates of walking and cycling: findings from the  
611 transportation, urban design, and planning literatures. *Ann Behav Med* 2003;**25**:80 - 91.
- 612 9. Saelens BE, Handy S. Built environment correlates of walking: a review. *Med Sci Sports Exerc*  
613 2008;**40**(7):550-66.
- 614 10. Bauman AE, Reis RS, Sallis JF, et al. Correlates of physical activity: why are some people  
615 physically active and others not? *Lancet* 2012;**380**(9838):258-71.

- 1  
2 616 11. McCormack G, Shiell A. In search of causality: a systematic review of the relationship  
3 617 between the built environment and physical activity among adults. *Int J Behav Nutr Phys*  
4 618 *Act* 2011;**8**(1):125.
- 5  
6 619 12. Briggs DC. Comments on Slavin: synthesizing causal inferences. *Educational Researcher*  
7 620 2008;**37**(1):15-22.
- 8  
9 621 13. Victora CG, Habicht J-P, Bryce J. Evidence-based public health: moving beyond randomized  
10 622 trials. *Am J Public Health* 2004;**94**(3):400-05.
- 11 623 14. Sallis JF, Owen N. Ecological models of health behavior. In: Glanz K, Lewis FM, Rimer BK,  
12 624 eds. *Health behaviour and health education: theory, research, and practice*. San Francisco:  
13 625 Jossey-Bass, 2002:462-84.
- 14  
15 626 15. Rychetnik L, Frommer M, Hawe P, et al. Criteria for evaluating evidence on public health  
16 627 interventions. *J Epidemiol Community Health* 2002;**56**(2):119-27.
- 17  
18 628 16. Ogilvie D, Bull F, Powell J, et al. An applied ecological framework for evaluating  
19 629 infrastructure to promote walking and cycling: the iConnect study. *Am J Public Health*  
20 630 2011;**101**:473–81.
- 21 631 17. Goodman A, Sahlqvist S, Ogilvie D, et al. New walking and cycling routes and increased  
22 632 physical activity: one- and two-year findings from the UK iConnect study. *Am J Public*  
23 633 *Health* 2014;**104**:e38-e46.
- 24  
25 634 18. Sahlqvist S, Goodman A, Jones T, et al. Mechanisms underpinning use of new walking and  
26 635 cycling infrastructure in different contexts: mixed-method analysis. *Int J Behav Nutr Phys*  
27 636 *Act*, **12**: 24.
- 28  
29 637 19. Ogilvie D, Bull F, Cooper A, et al. Evaluating the travel, physical activity and carbon impacts  
30 638 of a ‘natural experiment’ in the provision of new walking and cycling infrastructure:  
31 639 methods for the core module of the iConnect study. *BMJ Open* 2012;**2**:e000694.
- 32  
33 640 20. Adams E, Goad M, S. S, et al. Reliability and validity of the transport and physical activity  
34 641 questionnaire (TPAQ) for assessing physical activity behaviour. *PLoS One*  
35 642 2014;**9**(9):e107039.
- 36  
37 643 21. World Health Organisation. *Obesity: preventing and managing the global epidemic*. Geneva:  
38 644 World Health Organisation, 2000.
- 39 645 22. Pedhazur EJ. *Multiple regression in behavioral research: explanation and prediction (Third*  
40 646 *Edition)*. Fort Worth, Texas, USA Harcourt Brace., 1997.
- 41  
42 647 23. Bartlett M. The statistical conception of mental factors. *British Journal of Psychology*  
43 648 1937;**28**(97-104).
- 44  
45 649 24. Acock A. *A gentle introduction to Stata (Second Edition)*. College Station, Texas: Stata Press,  
46 650 2008.
- 47  
48 651 25. Muthén L, Muthén B. *Mplus User’s Guide*. Seventh Edition. Los Angeles, CA: Muthén &  
49 652 Muthén, 2012.
- 50 653 26. Golob TF. Structural equation modeling for travel behavior research. *Trans Res B*:  
51 654 2003;**37**(1):1-25.
- 52  
53 655 27. Goodman A, Sahlqvist S, Ogilvie D. Who uses new walking and cycling infrastructure and  
54 656 how? Longitudinal results from the UK iConnect study. *Prev Med* 2013;**57**(5):518-24.
- 55  
56 657 28. Kremers SPJ, Bruijn G, Visscher TLS, et al. Environmental influences on energy balance-  
57 658 related behaviors: a dual-process view. *Int J Behav Nutr Phys Act* 2006;**3**:9.
- 58  
59 659 29. Pope C, Ziebland S, Mays N. Analysing qualitative data. *BMJ* 2000;**320**(7227):114-16.
- 60



- 1  
2 660 30. Giles-Corti B, Timperio A, Bull F, et al. Understanding physical activity environmental  
3 661 correlates: increased specificity for ecological models. *Exercise Sport Sci R* 2005;**33**:175-  
4 662 81.
- 5  
6 663 31. Koohsari MJ, Sugiyama T, Lamb KE, et al. Street connectivity and walking for transport: Role  
7 664 of neighborhood destinations. *Prev Med* 2014;**66**:118-22.
- 8  
9 665 32. McCormack G, Spence J, Berry T, et al. Does perceived behavioral control mediate the  
10 666 association between perceptions of neighborhood walkability and moderate- and vigorous-  
11 667 intensity leisure-time physical activity? *J Phys Act Health* 2009;**6**(5):657-66.
- 12  
13 668 33. Timperio AF, van Stralen MM, Brug J, et al. Direct and indirect associations between the  
14 669 family physical activity environment and sports participation among 10-12 year-old  
15 670 European children: testing the EnRG framework in the ENERGY project. *Int J Behav Nutr*  
16 671 *Phys Act* 2013;**10**:15.
- 17  
18 672 34. Cousens S, Hargreaves J, Bonell C, et al. Alternatives to randomisation in the evaluation of  
19 673 public-health interventions: statistical analysis and causal inference. *J Epidemiol*  
20 674 *Community Health* 2011;**65**(7):576-81.
- 21  
22 675 35. Craig P, Cooper C, Gunnell D, et al. Using natural experiments to evaluate population health  
23 676 interventions: new Medical Research Council guidance. *J Epidemiol Community Health*  
24 677 2012;**66**(12):1182-6.
- 25  
26 678 36. Foster S, Knuiman M, Hooper P, et al. Do changes in residents' fear of crime impact their  
27 679 walking? Longitudinal results from RESIDE. *Prev Med* 2014;**62**:161-66.
- 28  
29 680 37. Adams E, Goodman A, Sahlqvist S, et al. Correlates of walking and cycling for transport and  
30 681 recreation: factor structure, reliability and behavioural associations of the perceptions of  
31 682 the environment in the neighbourhood scale (PENS). *Int J Behav Nutr Phys Act*  
32 683 2013;**10**(1):87.
- 33  
34 684 38. Strack F, Deutsch R. Reflective and Impulsive Determinants of social behavior. *Personality*  
35 685 *and Social Psychology Review* 2004;**8**(3):220-47.
- 36  
37 686 39. Hollands G, Shemilt I, Marteau T, et al. Altering micro-environments to change population  
38 687 health behaviour: towards an evidence base for choice architecture interventions. *BMC*  
39 688 *Public Health* 2013;**13**(1):1218.
- 40  
41 689 40. Thaler R, Sunstein C. *Nudge: improving decisions about health, wealth and happiness*. New  
42 690 Haven: Yale University Press 2008.
- 43  
44 691 41. Owen N, Humpel N, Leslie E, et al. Understanding environmental influences on walking;  
45 692 review and research agenda. *Am J Prev Med* 2004;**27**:67 - 76.
- 46  
47 693 42. National Institute for Health and Clinical Excellence. *Walking and cycling: local measures to*  
48 694 *promote walking and cycling as forms of travel or recreation*. London: National Institute  
49 695 *for Health and Clinical Excellence, 2012*.
- 50  
51 696 43. Pawson R, Tilley N. *Realistic Evaluation*. London, UK: Sage, 1997.
- 52  
53 697 44. Beenackers M, Kamphuis C, Mackenbach J, Burdorf A, van Lenthe F. Why some walk and  
54 698 others don't: exploring interactions of perceived safety and social neighborhood factors  
55 699 with psychosocial cognitions. *Health Educ. Res.*, 28 (2) (2013), pp. 220–233
- 56  
57 700 45. Hooper P, Giles-Corti B, Knuiman M. Evaluating the implementation and active living  
58 701 impacts of a state government planning policy designed to create walkable neighborhoods  
59 702 in Perth, Western Australia. *Am J Health Promotion* 2014;**28**(3 Suppl):S5-18.
- 60  
703 46. Rhodes R, Pfaeffli L. Mediators of physical activity behaviour change among adult non-  
704 clinical populations: a review update. *Int J Behav Nutr Phys Act* 2010;**7**(1):37.

1  
2 705  
3  
4 706  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

For peer review only

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

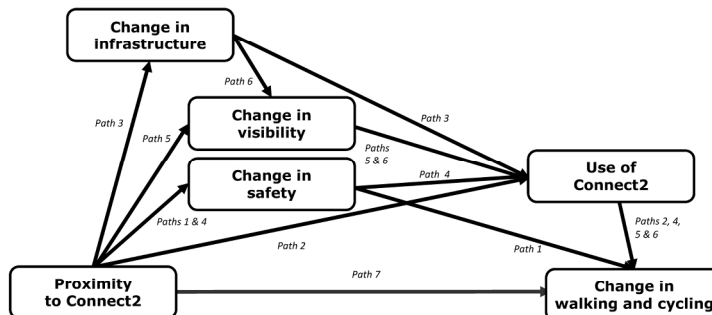
707 **Figure legend**

708 **Figure 1: Path models fitted in Mplus**

For peer review only

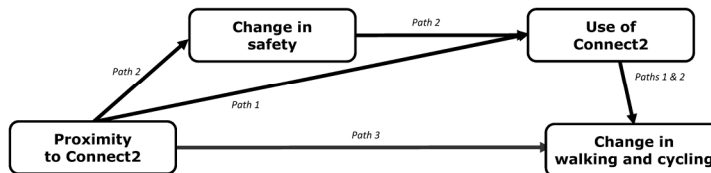
Figure 1: Path models fitted in Mplus

(a) Whole sample



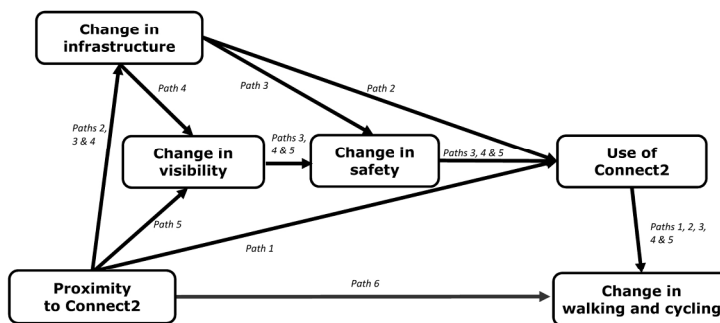
Path 1: indirect via safety only; path 2: indirect via use only; path 3: indirect via infrastructure and use; path 4: indirect via safety and use; path 5: indirect via visibility and use; path 6: indirect via infrastructure, visibility and use; path 7: direct path.

(b) Low-active subgroup



Path 1: indirect via use only; path 2: indirect via safety and use; path 3: direct path.

(c) High-active subgroup



Path 1: indirect via use only; path 2: indirect via infrastructure and use; path 3: indirect via infrastructure, safety and use; path 4: indirect via infrastructure, visibility, safety and use; path 5: visibility, safety and use; path 6: direct path.

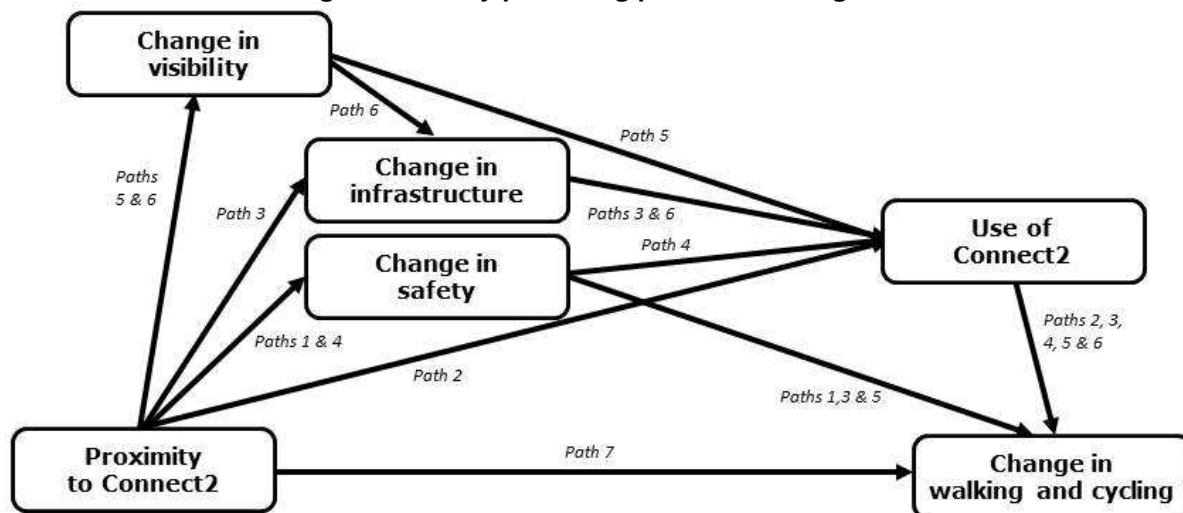
170x233mm (300 x 300 DPI)

Additional File 1: Factor analysis of perceived physical environmental items at baseline and follow-up

<b>Baseline</b>	Factor 1: 'Infrastructure'	Factor 2: 'Safety'	
Safety for walking	0.285	0.773	
Safety for cycling	0.256	0.794	
Pavements for walking	0.673	0.308	
Special lanes for cycling	0.748	0.256	
Pleasant	0.546	0.498	
Low crime	-0.209	0.715	
Lighting	0.770	-0.069	<i>n=1306</i>
Eigenvalue	3.01	1.23	
<b>Follow-up</b>			
Safety for walking	0.268	0.818	
Safety for cycling	0.258	0.804	
Pavements for walking	0.754	0.198	
Special lanes for cycling	0.759	0.236	
Pleasant	0.645	0.399	
Low crime	-0.066	0.763	
Lighting	0.763	0.006	<i>n=1310</i>
Eigenvalue	3.18	1.24	

Additional File 2: Results for alternative models with different ordering of mediators

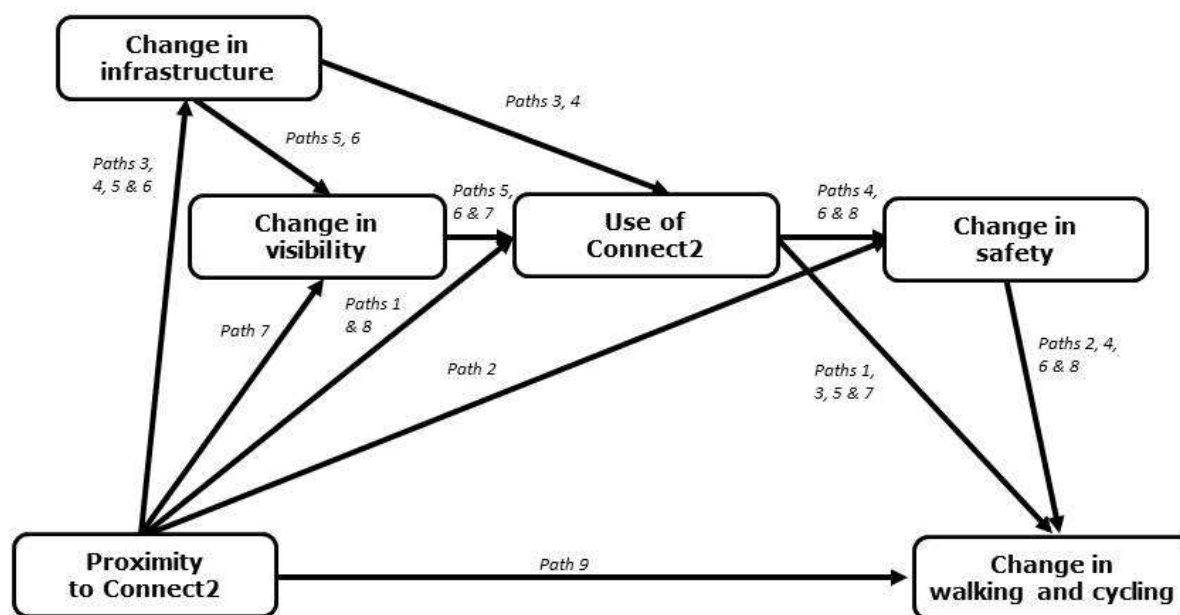
Alternative 1: Perceived change in visibility preceding perceived change in infrastructure



Path	$\beta$ (95% CI)	% of effect explained
Indirect via safety only (path 1)	2.25 (-7.14, 11.63)	4.5
Indirect via use only (path 2)	43.13 (22.09, 64.17)	86.2
Indirect via infrastructure and use (path 3)	1.26 (0.00, 2.51)	2.6
Indirect via safety and use (path 4)	1.38 (-0.04, 2.81)	2.8
Indirect via visibility and use (path 5)	0.84 (-0.10, 1.78)	1.6
Indirect via visibility, infrastructure and use (path 6)	0.08 (-0.03, 0.18)	0.2
Direct (path 7)	1.09 (-9.63, 11.81)	2.1
Total (sum of paths 1-7)	50.03 (27.61, 72.44)	100

Model shown above fitted using path analysis in Mplus, adjusted for time spent walking and cycling at baseline and the demographic, socioeconomic and health characteristics shown in Table 2

## Alternative 2: Perceived change in safety as a consequence of using the infrastructure



Path	$\beta$ (95% CI)	% of effect explained
Indirect via use only (path 1)	43.72 (22.47 to 64.96)	91.38
Indirect via safety only (path 2)	0.06 (-0.24 to 0.35)	0.11
Indirect via infrastructure and use (path 3)	1.4 (0.07 to 2.74)	2.93
Indirect via infrastructure, use and safety (path 4)	0.02 (-0.08 to 0.13)	0.05
Indirect via infrastructure, visibility and use (path 5)	0.07 (-0.02 to 0.15)	0.14
Indirect via infrastructure, visibility, use and safety (path 6)	0 (0 to 0.01)	0.01
Indirect via visibility and use (path 7)	0.78 (-0.13 to 1.69)	1.63
Indirect via use and safety (path 8)	0.69 (-2.48 to 3.87)	1.45
Direct (path 9)	1.1 (-9.62 to 11.82)	2.3
Total (sum of paths)	47.84 (26.62 to 69.06)	100

**Model shown above fitted** using path analysis in Mplus, adjusted for time spent walking and cycling at baseline and the demographic, socioeconomic and health characteristics shown in Table 2

## Additional File 3: Associations in low-active subgroup

<b>(a) Associations between proximity to and use of intervention</b>		
<b>Independent variable: Residential proximity to intervention (km)</b>		
<b>Dependent variable</b>	<b>OR (95% CI)</b>	<b>p</b>
Use of intervention (yes/no)	2.05 (1.68, 2.50)	0.001
<b>(b) Associations between use of intervention and changes in walking and cycling</b>		
<b>Independent variable: Use of intervention (yes/no)</b>		
<b>Dependent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in time spent walking and cycling (min/week)	62.96 (29.20, 96.71)	0.001
<b>(c) Associations between proximity to intervention and perceived environmental changes</b>		
<b>Independent variable: Residential proximity to intervention (km)</b>		
<b>Dependent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	0.05 (-0.02, 0.12)	0.153
Change in safety	0.08 (0.01, 0.15)	0.030
Change in visibility	0.01 (-0.05, 0.07)	0.804
<b>(d) Associations between perceived environmental changes and use of intervention</b>		
<b>Dependent variable: Use of intervention (yes/no)</b>		
<b>Independent variable</b>	<b>OR (95% CI)</b>	<b>p</b>
Change in infrastructure	1.12 (0.90, 1.40)	0.308
Change in safety	1.42 (1.12, 1.78)	0.001
Change in visibility	1.14 (0.91, 1.42)	0.240
<b>(e) Associations between perceived environmental changes and change in walking and cycling</b>		
<b>Dependent variable: Change in time spent walking and cycling (min/week)</b>		
<b>Independent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	-12.69 (-28.99, 3.61)	0.130
Change in safety	9.15 (-6.66, 24.97)	0.260
Change in visibility	-12.27 (-27.74, 3.20)	0.120
<b>(f) Associations between perceived environmental changes</b>		
<b>Dependent variable: Changes in visibility</b>		
<b>Independent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	0.02 (-0.06, 0.11)	0.596
Change in safety	0.04 (-0.04, 0.12)	0.341
<b>Dependent variable: Change in safety</b>		
<b>Independent variable</b>	<b><math>\beta</math> (95% CI)</b>	<b>p</b>
Change in infrastructure	-0.11 (-0.20, -0.01)	0.020

Linear or logistic regression models as appropriate adjusted for time spent walking and cycling at baseline and the demographic, socioeconomic and health characteristics shown in Table 2. Proximity was modelled as the negative of the distance between home and the nearest access point to the 'greater Connect2 project' including feeder routes. Each row represents a separate model which was not adjusted for the other mediators.



## Additional File 4: Associations in high-active subgroup

<b>(a) Associations between proximity to and use of intervention</b>		
<b>Independent variable: Residential proximity to intervention (km)</b>		
<b>Dependent variable</b>	<b>OR (95% CI)</b>	<b>p</b>
Use of intervention (yes/no)	1.79 (1.51, 2.11)	0.001
<b>(b) Associations between use of intervention and change in walking and cycling</b>		
<b>Independent variable: Use of intervention (yes/no)</b>		
<b>Dependent variable</b>	<b>β (95% CI)</b>	<b>P</b>
Change in time spent walking and cycling (min/week)	83.97 (34.65, 133.20)	0.001
<b>(c) Associations between proximity to intervention and perceived environmental changes</b>		
<b>Independent variable: Residential proximity to intervention (km)</b>		
<b>Dependent variable</b>	<b>β (95% CI)</b>	<b>p</b>
Change in infrastructure	0.06 (-0.01, 0.12)	0.076
Change in safety	0.00 (-0.07, 0.06)	0.951
Change in visibility	0.10 (0.04, 0.16)	0.001
<b>(d) Associations between perceived environmental changes and use of intervention</b>		
<b>Dependent variable: Use of intervention (yes/no)</b>		
<b>Independent variable</b>	<b>OR (95% CI)</b>	<b>p</b>
Change in infrastructure	1.36 (1.08, 1.72)	0.008
Change in safety	1.21 (0.97, 1.52)	0.089
Change in visibility	1.58 (1.27, 1.95)	0.001
<b>(e) Associations between perceived environmental changes and change in walking and cycling</b>		
<b>Dependent variable: Change in time spent walking and cycling (min/week)</b>		
<b>Independent variable</b>	<b>β (95% CI)</b>	<b>p</b>
Change in infrastructure	5.02 (-20.08, 30.12)	0.695
Change in safety	9.00 (-16.76, 34.76)	0.493
Change in visibility	3.66 (-21.05, 28.37)	0.771
<b>(f) Associations between physical and social environmental changes</b>		
<b>Dependent variable: Change in visibility of walking and cycling</b>		
<b>Independent variable</b>	<b>β (95% CI)</b>	<b>p</b>
Change in infrastructure	0.11 (0.02, 0.20)	0.020
Change in safety	0.03 (-0.06, 0.12)	0.580
<b>Dependent variable: Change in safety</b>		
<b>Independent variable</b>	<b>β (95% CI)</b>	<b>p</b>
Change in infrastructure	0.06 (-0.03, 0.15)	0.188

Linear or logistic regression models as appropriate adjusted for time spent walking and cycling at baseline and the demographic, socioeconomic and health characteristics shown in Table 2. Proximity was modelled as the negative of the distance between home and the nearest access point to the 'greater Connect2 project' including feeder routes. Each row represents a separate model which was not adjusted for the other mediators.

**Additional File 5: Contributions of different pathways to behaviour change in those with (a) a low and (b) a high level of walking and cycling at baseline**

	$\beta$ 95%CI
<b>(a) Low-active subgroup</b>	
Indirect via use only (path 1)	40.0 (10.17, 69.92)
Indirect via safety and use (path 2)	2.3 (-0.28, 4.87)
Direct (path 3)	0.0 (-13.28, 12.74)
Total (sum of paths 1-3)	42.3 (12.4, 71.74)
<b>(b) High-active subgroup</b>	
Indirect via use only (path 1)	48.62 (15.66 to 81.58)
Indirect via infrastructure and use (path 2)	0.22 (-0.5 to 0.94)
Indirect via infrastructure, safety and use (path 3)	0 (0 to 0)
Indirect via infrastructure, visibility, safety and use (path 4)	0 (-0.12 to 0.12)
Indirect via visibility, safety and use (path 5)	0 (-0.35 to 0.35)
Direct (path 6)	1.1 (-17.09 to 19.29)
Total (sum of paths 1-6)	49.94 (17.58 to 82.3)

**Models shown in Figures 1 (b) and (c) respectively fitted** using path analysis in Mplus, adjusted for time spent walking and cycling at baseline and the demographic, socioeconomic and health characteristics shown in Table 2.

STROBE Statement—Checklist of items that should be included in reports of cohort studies

Section/Topic	Item #	Recommendation	Reported on page #
Title and abstract	1	(a) Indicate the study’s design with a commonly used term in the title or the abstract	1
		(b) Provide in the abstract an informative and balanced summary of what was done and what was found	2
<b>Introduction</b>			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	3-4
Objectives	3	State specific objectives, including any prespecified hypotheses	5
<b>Methods</b>			
Study design	4	Present key elements of study design early in the paper	5
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	5-6
Participants	6	(a) Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up	5-6
		(b) For matched studies, give matching criteria and number of exposed and unexposed	N/A
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	6-9
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	6-9
Bias	9	Describe any efforts to address potential sources of bias	N/A
Study size	10	Explain how the study size was arrived at	11
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	11
Statistical methods	12	(a) Describe all statistical methods, including those used to control for confounding	11
		(b) Describe any methods used to examine subgroups and interactions	11
		(c) Explain how missing data were addressed	11
		(d) If applicable, explain how loss to follow-up was addressed	N/A
		(e) Describe any sensitivity analyses	N/A
<b>Results</b>			

Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	11
		(b) Give reasons for non-participation at each stage	11
		(c) Consider use of a flow diagram	N/A
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	13
		(b) Indicate number of participants with missing data for each variable of interest	13
		(c) Summarise follow-up time (eg, average and total amount)	5
Outcome data	15*	Report numbers of outcome events or summary measures over time	N/A
Main results	16	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	15
		(b) Report category boundaries when continuous variables were categorized	13
		(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	N/A
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	17, 18 and Additional file
<b>Discussion</b>			
Key results	18	Summarise key results with reference to study objectives	19
<b>Limitations</b>			
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	21-22
Generalisability	21	Discuss the generalisability (external validity) of the study results	20
<b>Other information</b>			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	26

\*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

**Note:** An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at <http://www.plosmedicine.org/>, Annals of Internal Medicine at <http://www.annals.org/>, and Epidemiology at <http://www.epidem.com/>). Information on the STROBE Initiative is available at [www.strobe-statement.org](http://www.strobe-statement.org).