Longitudinal effects of urban green space on walking and cycling: A fixed effects analysis

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ABSTRACT

This study examined whether changes in green space within the living environment were associated with changes in walking and cycling frequencies in a cohort of 3,220 Dutch adults between 2004, 2011 and 2014. Data on self-reported weekly time spent walking and cycling for active commute and leisure were linked to geographic information system (GIS) measures of total green areas within 1000 m buffer zones around each participant's home address, and distance to the nearest green space. First, cross-sectional linear regression models showed no statistically significant associations between green space measures and walking and cycling. Second, fixed effects (FE) models were used to analyze whether changes in green space were associated with changes in walking and cycling, using longitudinal data from respondents who did not relocate over time. As distance to the nearest green area increased by 100 m, individuals spent 22.76 fewer (95% CI: −39.92, −5.60) minutes walking for leisure per week and 3.21 more (95% CI: 0.46, 5.96) minutes walking for active commute. Changes in distance to green space were not significantly related to changes in cycling measures. No clear associations between changes in green areas within 1000 m buffers and changes in walking and cycling were observed. Overall, there was weak evidence of an effect of changes in green space area on changes in walking, and no evidence for cycling.

1. Background

The urban landscape can shape human activity and offer avenues for health promotion. Current trends in overconsumption and sedentary lifestyles contribute to the prevalence of non-communicable diseases (NCDs), accounting for 70% of deaths worldwide and inflicting strain on health, societal, and economic systems. Increased physical activity (PA) is cited as a top priority intervention in curbing the detrimental effects of chronic disease (Beaglehole et al., 2011) by increasing longevity and protecting against cardiovascular diseases, site-specific cancers, type 2 diabetes, obesity, osteoporosis, metabolic syndrome, and high blood cholesterol (Wang et al., 2016; Myers et al., 2015). While many public health efforts focus on conscious behavior change to increase PA, the built environment has been shown to have an effective role in encouraging activity (Sugiyama et al., 2018; MacMillan et al., 2018; Brownson et al., 2009). A spatial-analysis of residential vicinities can inform public

policies on how best to influence the health of a population.

Walking is recognized among the most common, acceptable, and accessible forms of physical activity across different age groups, gender, and ethnicities (Siegel et al., 1995). Along with cycling, it can be used for commute and leisure purposes to habitually increase daily energy expenditure and improve health (Kerr et al., 2016). The Netherlands offers a unique case study given the high prevalence of commuter walking and cycling, with 25% of all journeys being traveled by bicycle (Gao et al., 2017). Given a cultural predisposition to an active commute, what stimulates or demotivates Dutch adults to walk or cycle? More importantly, how can cities spatially adapt to further increase activity on a population level?

Emerging socio-ecological approaches have focused on the importance of the built environment in shaping health and behavior. Studies often cite street connectivity, land use mix, neighborhood safety, traffic, access to facilities and parks, landscape, and others, as relevant aspects of an active commute (de Vries et al., 2010). However, unlike countries

Abbreviations

FE	Fixed effects
GIS	Geographic Information System
GLOBE	Gezondheid en LevensOmstandigheden Bevolking Eindhoven en omstreken
ISCED	International Standard Classification of Education
NCD	Non-communicable disease
PA	Physical activity
SQUASH	Short Questionnaire to Assess Health enhancing physical activity
WHO	World Health Organization

like the United States or Australia in which many of these studies have been conducted, the Netherlands offers a pedestrian and cyclist friendly infrastructure featuring extensive cycling rights of way, bicycle lanes and parking, and educational training for cyclists and motorists (Pucher and Buehler, 2008). Exploring other characteristics, such as the availability of green space, may therefore prove more fruitful in decoding the health-place relationship.

Increased green space has been associated with reduced adult mortality (van den Berg et al., 2015), improved social capital, and lower stress (Mitchell and Popham, 2008; Groenewegen et al., 2012). A recent report by the World Health Organization (WHO) lists pathways linking green space to a multitude of health outcomes (Egorov et al., 2016), and positive associations have been shown between the quantity and quality of urban green areas in relation to small-area life expectancy (Jonker et al., 2014). A review by Hartig et al. details varying and mixed effects on active and leisure transport (Hartig et al., 2014). In terms of accessibility and usage, an increase in distance to green space is linked with a decline in its use (Nielsen and Hansen, 2007). In addition, quality features and facilities might carry more importance in determining whether residents utilize green areas (Kaczynski et al., 2008).

While some cross-sectional analyses tout significant associations between green space and PA (Kaczynski et al., 2009; Lachowycz and Jones, 2011) they cannot assess a temporal relationship between exposure and outcome. Thus, causality cannot be established, putting in question the strength and robustness of these observations. Many studies do adjust for confounding factors, but it remains unclear which factors should be included to effectively account for selection (van den Berg et al., 2015). Individuals may choose to live in certain neighborhoods based on lifestyle preferences, environmental considerations, and economic or social factors. The deliberate choice of a physically active person to live in a neighborhood with more green space, for instance, will inflate the association observed between the environment and physical activity in a cross-sectional study. Statistical methods to account for these concerns exist, but have not been widely applied, and the complex nature and interacting features of environmental factors, health, and other variables make it difficult to extricate underlying mechanisms (Egorov et al., 2016). A few studies explore the effects of longitudinal changes in the built environment (Giles-Corti et al., 2013; Knuiman et al., 2014; Panter et al., 2013; Christian et al., 2017) and specifically green space (Sugiyama et al., 2013; McCormack et al., 2010; Gubbels et al., 2016) on physical activity measures, but none over a substantial time period with the use of historical green space data and specific, continuous measures of activity such as walking and cycling. Our study offers a unique approach by analyzing longitudinal data with fixed effects (FE) models that rely on within-individual changes to control for confounding. FE models can allow researchers to estimate causal effects from panel data without the need to measure all possible characteristics, as long as these factors do not change over time (i.e. they are "fixed"). This effectively reduces the burden of confounding, and controls for selection effects (White et al., 2013). To the extent that an

individual's choice to select into a neighborhood and potential confounding factors do not change over time (i.e. to the extent that they can be considered to be "fixed effects"), the FE approach is well suited to observe unbiased effects. Moreover, gaining ground on before-and-after effects of environmental change has greater practical relevance in public health policy. While traditional studies describe associations that exist in a moment, FE analyses can strengthen the basis for causal inference by considering whether a change in green space may lead to a change in physical activity. Ultimately, causal evidence may be a cause for action.

This paper aims to decode causal relationships between green space and frequency of walking and cycling by linking comprehensive GIS measures of green space area and proximity to physical activity outcomes from cohort data with 10 years of follow-up. We first describe group-level associations deduced from a cross-sectional analysis. Next, we explore within-subject changes with a fixed effects model. Lastly, we estimate within-subject changes among participants that did not relocate during follow-up.

2. Methods

2.1. Study population

Data was obtained from GLOBE, a prospective cohort study on socioeconomic health inequalities in the Netherlands. The study surveyed adults living in the city of Eindhoven and surrounding areas, a sample representative of the Netherlands as a whole in terms of age, gender, and level of education. Baseline health questionnaires were distributed in 1991 to a random sample of 27,070 individuals aged 15–75 years old, with an overall response rate of 70.1%. The postal questionnaires assessed health, material, behavioral, psychological, and environmental factors indicative of socioeconomic and health disparities. Additional details of the Dutch GLOBE study can be found elsewhere (van Lenthe et al., 2014). The 2004 sample of GLOBE participants representative of the source population of residents aged 25–75 years who resided in Eindhoven and surroundings were selected for the analyses (N = 4,758). Additional questionnaires were administered in 2011 and 2014 (but not in intermediate years). Given that fixed-effects analyses require at least two measurements, respondents who only participated in one year were excluded (30%), resulting in a sample of 3,340 respondents. Analyses were restricted to individuals who resided in Eindhoven and surrounding municipalities at the waves they participated in, and who could be successfully geocoded, resulting in a final sample of 3,220 participants of which 62.8% had measures for all three waves (2004: N = 3,220; 2011: N = 2,884; 2014: N = 2,382).

2.2. Outcome measures of walking and cycling

Self-reported measures of walking and cycling were assessed using the validated SQUASH (Short Questionnaire to Assess Health enhancing physical activity), a tool created by the Dutch National Institute of Public Health and the Environment to measure habitual physical activity levels in an adult population. This simple questionnaire offers a reliable evaluation of physical activity in large populations (Wendel-Vos et al., 2003). Participants reported average number of days per week, and hours and minutes per day, spent walking and cycling as part of an active commute and for leisure purposes. Following SQUASH-guidelines, it was assumed that all participants who filled in hours or minutes per week, but omitted 'days per week,' had been active for at least one day. Further, if the number of days was provided without a corresponding time frequency, the median minutes per day of all respondents was substituted, and a final measure of minutes per week was computed. Variables were recoded into separate measures for walking and cycling for active commute, and leisure, as well as total frequencies.

2.3. Exposure measures of green space

The main explanatory variables used included the total area of green space in the living environment, and distance to the nearest green space. GLOBE cohort data from the 2004 and 2011 waves was linked with geographical data from 2003 and 2010 respectively, keeping in line with an appropriate chronology of exposure preceding outcome measures. The 2014 GLOBE cohort data was linked with 2012 geographical data as 2013 geographical data was not available. Respondent addresses were geocoded using geographical software package QGIS and a geocoding plug-in developed by the Dutch National Spatial Data Infrastructure (PDOK) (Dutch National; QGIS Development Team, 2017). To maintain respondent privacy, addresses were extracted and geo-coded using a process previously described (Rodgers et al., 2012; Beenackers et al., 2018). In total, 98% of addresses were successfully geo-coded. Movement to a different address between follow-up years was recorded.

Historical geographic data of Eindhoven and surrounding areas was obtained from the Dutch dataset 'Bestand Bodemgebruik' (BBG), created by Statistics Netherlands (CBS). The BBG is a harmonized dataset based on "Top10NL" digital 1:10,000 topographic maps provided by Dutch mapping agency Kadaster, and is available as free, open source GIS files. Each BBG data release is based on the most recently available topographical data from that year. Furthermore, whenever a new wave of the BBG data is released, all previous data waves are updated using the most recent processing techniques. The time-varying exposure variables of green space were calculated at each wave. The harmonization of the BBG data ensures that observed changes in green spaces are representative of actual changes in the built environment and not related to changes in GIS processing. Extensive land classification data was used to locate categories of green spaces relevant to walking and cycling, including parks, sports areas, allotment gardens, recreational areas, agricultural land, forests, and dry and wet open terrain. The absolute distance from the participant's home to the nearest point on the boundary of a green space was measured and recorded for each participant at each time point in QGIS. The total area of green space was calculated within an Euclidian buffer of 1000 m (area 314.16 ha) from geo-coded addresses using QGIS. This buffer represents a large enough area around the home suitable for physical activity, roughly equivalent to 15–20 min of walking and is comparable to measures in previous research (Egorov et al., 2016; Klompmaker et al., 2018; Maas et al., 2008; Su et al., 2011; Wolch et al., 2011). A review analyzing GIS buffer measures of green space suggests that larger buffers better predict physical health than smaller ones (Browning and Lee, 2017), informing our selection of a 1000 m buffer to measure potential effects on both walking and cycling.

2.4. Covariates

Marital status (married/partnership, not married, divorced, widowed), annual household income (monthly; <€1200, €1200–1800, €1800–2600, >€2600) employment status (employed, unemployed, retired, non-employed), smoking status (current, former, or never smoker), and self-rated health (excellent, very good, good, fair, poor) were included as relevant time-varying confounders that may play a role in physical activity outcomes. All covariates were measured at all time points, capturing changes that occurred in the ten-year period. Time-invariant characteristics (measured in 2004) included in the cross-sectional analyses were age, gender (male, female), birthplace (Netherlands, elsewhere), and education (lowest = ISCED 0–1, low = ISCED 2, middle = ISCED 3–4, high = ISCED 5–7).

2.5. Statistical analysis

Missing data on covariates (missingness ranged from 0% [gender and age] to 7% [employment], and up to 26% for household income in 2014) were handled via multiple imputation (M = 20) using all variables listed above and several other variables, such as educational level, place of birth, marital status, smoking status, and self rated health. Outcome variables were not imputed (10.5% missing on walking/cycling for active commute, 7.0% missing on walking/cycling for leisure, 13.1% missing on total walking/cycling). No missing data were present on the exposures (i.e. GIS-measures could be calculated for all geocoded participants).

First, cross-sectional analyses were performed separately on data from 2004 on the full sample of 3,220 participants. Associations between exposure and outcome were explored with linear regression models adjusted for age, age squared, gender, birthplace, education, marital status, income, employment, smoking, and self-rated health.

Second, fixed effects (FE) models (using data from 2004, 2011 and 2014) were used to estimate the relationship between within-person change in urban green areas in the living environment, and within-person change in walking and cycling outcomes on data restricted to participants who did not relocate during follow-up (N = 2,850). An FE analysis controls for potential confounders that do not change over time, but vary between individuals, such as gender, place of birth, and highest level of education. Provided that changes are observed, the FE model is able to capture to what extent changes in green space exposure between time-points is related to changes in walking and cycling frequencies between time-points.

Two FE models were applied: a linear regression model controlling for time only, and an adjusted model with additional controls for time-varying characteristics of marital status, employment, income, smoking, and self-rated health. The following model was used for the analyses:

$$\text{Walking/cycling}_{it} = \mu_t + \beta_1 \text{ green space}_{it} + \beta_2\, x_{it} + \alpha_i + \varepsilon_{it}$$

where $Walking/cycling_{it}$ indicates the walking/cycling frequency for individual i at time t, $green space_{it}$ represents the green space area within separate buffer zones or distance to nearest green space, x_{it} is a vector of time-varying control regressors, and ε_{it} is the error term. μ_t accounts for time effects that are fixed for all individuals, while α_i controls for time-invariant personal characteristics.

Robust standard errors were used to account for non-independence clustering at the individual level. Analyses were performed using STATA 13 (StataCorp. Stata Statisti, 2013).

3. Results

3.1. Sample characteristics

Participant demographic characteristics are presented in Table 1. The final sample consisted of 3,220 adults of mostly Dutch origin residing in Eindhoven and surrounding areas. The mean follow-up time was 9.2 years. The baseline mean age in 2004 was 53 years; 56% of the participants were women. A little over half of all respondents completed a middle-to-high level of education. On average, respondents walked for 160 min per week and cycled for 150 min per week, spending 66% more time on leisure travel as compared to active travel to work or school. In 2004, respondents resided an average distance of 193 m from the nearest green space. Participants were surrounded by an average green area of 47.6 ha (15%) within a 1000 m buffer around their home address.

3.2. Cross-sectional analyses

Linear regression models applied to cross-sectional data in 2004 showed non-significant and negligible associations between distance to green space and time spent walking and cycling, as shown in Table 2. Similarly, the area of green space was not significantly associated with outcome measures, and results showed wide confidence intervals.

Table 1
Description of the study population in 2004 (n = 3,220).

Variables	Mean (SD) /%
Exposures	
Distance to green space (m)	193 (139)
Green space within a 1000 m buffer (ha)	47.6 (27.7)
Walking and cycling (min/week)	
Walking for transport	13 (59)
Cycling for transport	39 (87)
Walking for leisure	147 (198)
Cycling for leisure	110 (170)
Walking and cycling for transport	52 (111)
Walking and cycling for leisure	257 (282)
Total walking	160 (211)
Total cycling	150 (198)
Total walking and cycling	310 (309)
Time fixed characteristics	
Age, mean (SD)	53 (Mitchell and Popham, 2008)
Male, %	44
Born in The Netherlands, %	93
Educational level	
High, %	31
Middle, %	25
Low, %	35
Lowest, %	9
Time varying characteristics	
Marital status	
Married/partnership, %	76
Unmarried, %	12
Divorced, %	7
Widowed, %	5
Employment	
Employed, %	50
Unemployed, %	7
Retired, %	26
Non-employed, %	17
Smoking status	
Never smoked, %	42
Former smoker, %	38
Current smoker, %	20
Household income per month	
<€1200, %	33
€1200–1800, %	29
€1800–2600, %	25
€2600–4000, %	13
Self-rated health	
Excellent, %	8
Very good, %	22
Good, %	55
Fair, %	14
Poor, %	1

3.3. Within-person changes

Within-person changes were observed for all exposures and outcomes, consisting of both increases and decreases in measures over time (Table 3). For the green space measures, about two-thirds of the 6,158 available person observations exhibited changes in distance to nearest green space and changes in green area within a 1000 m buffer. For walking and cycling outcomes, changes were particularly small for active commute measures, with only 14% and 30% of within-person changes over time for walking and cycling, respectively. For leisure walking and cycling, changes were considerably more frequent (81% and 74% respectively). There was an average positive change in total walking and cycling (increase of 16.84 min per week). Average time spent on leisure activities increased by 19.84 min per week, whereas total active commute measures saw a decrease by 2.68 min per week.

3.4. Fixed effects analyses

Table 4 presents results from fixed effects regression analyses using only data from respondents who did not relocate between years. An increase of 100 m in distance to the nearest green space was related to

Table 2
Linear regression models regressing walking and cycling measures (in minutes per week) on green space using cross-sectional data from 2004 (n = 3,220).

	Beta	95% CI		p-value
Distance to nearest green space (100 m)				
Walking for transport	0.32	−1.16	1.79	0.674
Cycling for transport	−0.23	−2.33	1.87	0.828
Walking for leisure	0.65	−4.33	5.64	0.797
Cycling for leisure	−2.92	−7.09	1.25	0.169
Walking and cycling for transport	0.08	−2.63	2.80	0.952
Walking and cycling for leisure	−2.27	−9.17	4.64	0.519
Total walking	0.90	−4.43	6.23	0.740
Total cycling	−3.39	−8.37	1.60	0.183
Total walking and cycling	−2.48	−10.20	5.23	0.528
Green space within 1000m buffer (ha)				
Walking for transport	−4.84	−12.25	2.57	0.201
Cycling for transport	8.49	−2.08	19.05	0.115
Walking for leisure	6.59	−18.28	31.45	0.603
Cycling for leisure	3.13	−17.66	23.92	0.768
Walking and cycling for transport	3.65	−10.03	17.32	0.601
Walking and cycling for leisure	9.72	−24.71	44.15	0.580
Total walking	2.07	−24.54	28.67	0.879
Total cycling	11.07	−13.80	35.94	0.383
Total walking and cycling	13.14	−25.33	51.61	0.503

*Adjusted for age, age squared, sex, birthplace, education, marital status, income, employment, smoking and self-rated health.

Table 3
Within-person changes in green space and walking and cycling between 2004, 2011 and 2014.

	Decrease	No Change	Increase	Average change
	Mean (N)	Mean (N)	Mean (N)	Mean (N)
Participants that did not relocate between years (N = 6,158 person observations)				
Distance to nearest GS (m)	−23.34 (N = 2166)	0 (N = 1846)	28.76 (N = 2146)	1.81 (N = 6158)
1000 m buffer (ha)	−5.45 (N = 2228)	0 (N = 1668)	4.78 (N = 2262)	−0.22 (N = 6158)
Walking for active commute	−127.74 (N = 386)	0 (N = 4697)	147.04 (N = 395)	1.60 (N = 5478)
Cycling for active commute	−132.79 (N = 902)	0 (N = 3834)	129.85 (N = 742)	−4.28 (N = 5478)
Walking for leisure	−174.04 (N = 2097)	0 (N = 1099)	176.65 (N = 2519)	14.00 (N = 5715)
Cycling for leisure	−155.42 (N = 2058)	0 (N = 1492)	163.14 (N = 2165)	5.83 (N = 5715)
Total active commute	−150.02 (N = 1072)	0 (N = 3484)	158.52 (N = 922)	−2.68 (N = 5478)
Total leisure	−225.44 (N = 2410)	0 (N = 457)	230.57 (N = 2848)	19.84 (N = 5715)
Total walking	−180.11 (N = 2009)	0 (N = 940)	185.05 (N = 2374)	14.55 (N = 5323)
Total cycling	−173.27 (N = 2064)	0 (N = 1196)	179.27 (N = 2063)	2.29 (N = 5323)
Total walking and cycling	−239.42 (N = 2349)	0 (N = 354)	248.88 (N = 2620)	16.84 (N = 5323)

more walking for commute (β 3.21, 95% CI 0.46, 5.96), and less walking for leisure (β −22.76, 95% CI −39.92, −5.60) and total walking (β −21.37, 95% CI −38.87, −3.88). Greater distance was related to less time spent walking and cycling (β −22.36, 95% CI −46.19, 1.48), but confidence intervals included the null.

Walking for commute decreased with each additional hectare of green space in the 1000 m buffer (β −33.84, 95% CI −67.90, 0.23). Meanwhile, increases in green space area seemed to be associated with additional minutes spent walking for leisure (β 58.42, 95% CI −74.22, 191.06), but confidence intervals included the null. When combined, the measure of total walking minutes was not significantly related to the area of green space in the 1000 m buffer (β 39.46, 95% CI −98.22, 177.14). Minutes spent cycling, and combined measures of all outcomes,

Table 4
Fixed effects linear regression models regressing changes in walking and cycling measures (in minutes per week) on changes in green space using data from 2004, 2011 and 2014 and restricted to participants who did not relocate during follow-up (n = 6,158 person observations).

	Crude model				Adjusted model[a]			
	Beta	95% CI		p	Beta	95% CI		p
Distance to nearest GS (100 m)								
Walking for active commute	3.42	0.68	6.15	0.014	3.21	0.46	5.96	0.022
Cycling for active commute	−2.92	−8.06	2.22	0.265	−2.08	−7.21	3.05	0.427
Walking for leisure	−20.78	−38.19	−3.37	0.019	−22.76	−39.92	−5.60	0.009
Cycling for leisure	3.43	−12.44	19.31	0.671	2.22	−13.50	17.93	0.782
Total active commute	0.50	−5.36	6.35	0.868	1.13	−4.72	6.98	0.705
Total leisure	−17.34	−41.70	7.01	0.163	−20.55	−44.22	3.13	0.089
Total walking	−19.30	−37.02	−1.57	0.033	−21.37	−38.87	−3.88	0.017
Total cycling	−1.03	−17.10	15.04	0.900	−0.98	−16.89	14.92	0.904
Total walking and cycling	−20.33	−44.46	3.80	0.099	−22.36	−46.19	1.48	0.066
1000m buffer (ha)								
Walking for active commute	−32.99	−67.10	1.12	0.058	−33.84	−67.90	0.23	0.052
Cycling for active commute	8.64	−49.29	66.57	0.770	10.30	−45.88	66.48	0.719
Walking for leisure	50.08	−82.40	182.57	0.459	58.42	−74.22	191.06	0.388
Cycling for leisure	−51.84	−164.76	61.08	0.368	−50.22	−162.04	61.60	0.379
Total active commute	−24.35	−92.57	43.87	0.484	−23.54	−89.79	42.71	0.486
Total leisure	−1.76	−174.74	171.22	0.984	8.20	−163.26	179.66	0.925
Total walking	30.67	−106.83	168.16	0.662	39.46	−98.22	177.14	0.574
Total cycling	−40.34	−162.07	81.38	0.516	−38.64	−160.18	82.90	0.533
Total walking and cycling	−9.68	−188.70	169.35	0.916	0.82	−178.84	180.48	0.993

[a] Adjusted for marital status, income, employment, smoking and self-rated health.

were also not significantly related to green space.

4. Discussion

This study examined whether changes in green space within the living environment were associated with changes in walking and cycling frequencies over a ten-year period. An initial cross-sectional analysis of baseline data did not show significant associations between green space proximity and the amount of green space within the living environment, and weekly walking and cycling. Fixed effects analysis restricted to participants that did not relocate during follow-up suggested that as distance to the nearest green area increased, individuals decreased their walking frequency, with no relation to changes in cycling measures. No clear associations between changes in green areas within 1000 m buffers and changes in walking and cycling were observed. There was weak evidence overall of an effect of changes in green space area on changes in walking, and no evidence for cycling.

Urban green space has widely been endorsed with health-promoting benefits, with positive associations found between nearby parks and overall health and physical activity (Douglas et al., 2017). Recent policy frameworks, notably the United Nations' *Habitat III* New Urban Agenda, also support the greening of urban areas as a means toward physical and mental health promotion (Douglas et al., 2017). However, literature offers mixed results regarding the role of urban green space on physical activity due to variation in methodological approaches, measurement of physical activity (Kaczynski et al., 2008), and the characterization of relevant green space (Markevych et al., 2017; Meurs and Haaijer, 2001). The current study is one of few longitudinal analyses which models estimated effects of green space change on the most common, and accessible forms of physical activity: walking and cycling. It fills an important methodological gap by aiming to interpret the relationship between health and place in a way that has more potential for evidence-based action.

Our baseline analysis found weak, non-significant associations between green space and activity levels, which is comparable to findings of Maas et al. (2008). In contrast, the longitudinal fixed effects analysis among participants that did not relocate during follow-up showed that changes in residential proximity to green space significantly impacted walking frequency; an increase of 100 m to the nearest green space resulted in 21 fewer minutes per week spent walking overall, 23 fewer

minutes of leisure walking, but 3 additional minutes walking for commute. Previous research has shown that green space within walking distance of the home generally supports human health (Ekkel and de Vries, 2017), while parks located further away are not as likely to be used (Coombes, 1982). While no official cut-off distance is supported by empirical evidence, Annerstedt van den Bosch et al. have proposed a guideline of 1 ha within a 300 m absolute distance to the nearest green space as a green space indicator for public health (Annerstedt van den Bosch et al., 2016). Other studies also cite distance as a key determinant of green space use, with 100–300 m appearing as the threshold beyond which a decline in use is observed (Nielsen and Hansen, 2007). Our findings suggest that introducing green space closer to one's residence can encourage people to spend more time walking for leisure, but not as part of their commute. Green space closer to the home may deter individuals from walking to work or school, and instead encourage cycling or driving. This observed effect may also relate to the cohort demographic and nature of the activity; members of an ageing cohort gradually enter retirement, thus eliminating the necessity of walking to work, and this in turn can skew the FE model to produce significant results.

Whereas walking seemed to be affected by changes in green space, cycling was not. Moreover, in relation to the changes in green area in 1000 m buffer, no significant associations were observed for total measures of walking and cycling. This lack of significant associations suggests that additional factors may be more important for physical activity than changes in green space. Walking and cycling can depend on personal preferences and constraints. An aging generation will likely be faced with different demands, for example, familial obligations such as caring for grandchildren. The mechanisms linking walking and cycling to green space availability are also likely influenced by other factors in the home environment. For instance, factors such as crime, safety, deprivation, social interaction, road safety, and particularly a pedestrian and cyclist friendly urban environment in the Netherlands, may affect whether or not people walk or cycle in nearby green areas, and may have limited or tempered any effects of changes in green space on changes in activity. This may be particularly pronounced for cycling, considering the wide availability and use of bike lanes in The Netherlands (Evenson et al., 2012; Foster et al., 2016; Weimann et al., 2017; Carver et al., 2005). Furthermore, the choice of buffer sizes in measuring total area of green space may play a role in the strength and significance of the

results.

4.1. Strengths and limitations

The original contribution of this study is the multi-methodological approach and use of detailed GIS data, enabling the linkage of changes in environment and behavior. Much of previous research has relied on wider scale, neighborhood or city-level data that does not accurately depict within-subject changes in exposure. The data provided by the BBG allowed for precise calculations of total green space area and identification of actual changes over time that are not affected by changes in GIS processing. Euclidian buffers around respondents' homes aided in reducing spatial misclassification faced by other indicators, such as neighborhood boundaries (Hirsch et al., 2014), and the choice of a 1000 m buffer was comparable to other studies. Further, data from the GLOBE study offered detailed measures of personal characteristics that were used to control for time-varying confounding. The use of multiple outcomes based on a validated questionnaire offered insight into how specific activities are affected by factors in the environment, discerning between commuting and leisure activities, and modes of walking and cycling.

A main limitation of this study is the low within-person variability in walking and cycling for active commute, which restricts the statistical efficiency of a fixed-effects analysis. Although FE analyses are better able to infer causality, they are dependent on observable changes in exposure and outcome measures. The current FE models may have not been able to depict significant relationships due to limited changes observed in the sample population. Further, baseline characteristics reflect a generally active, healthy, and affluent sample of individuals, which may influence how they react to changes in the built environment. For instance, aspects such as car ownership, or the propensity for an active lifestyle, can minimize the impact of de-greening a neighborhood. In addition, around one quarter of missing baseline data on household income was imputed, with implications for biased effect estimates if data was not missing at random. Our statistical model assumes no correlation of attrition and missingness to unmeasured, time-varying characteristics in the study sample, but, if violated, this correlation may have biased the results. In addition, the assumption that the residuals of the linear regression model are normally distributed was violated in the cross-sectional analysis for the active commute measures. However, using negative binomial regression models did not change the findings. Moreover, the fixed effects models did not suffer from this limitation (changes in walking and cycling were mostly normally distributed). We therefore reported results from the linear regression models only.

Self-reported measures of walking and cycling, though based on a validated questionnaire, are subject to recall bias if older participants struggle to provide accurate measures of physical activity. In addition, while our GIS data offered an accurate measure of existing green space, there is no evidence for the actual use or even awareness of these green areas by participants. Similarly, the nearest green space to an individual's home address may not be perceived as such, given its size or functionality, and Euclidian distances may not reflect the travel routes taken by participants.

4.2. Future research

To better understand environmental influences on walking and cycling, prospective studies should incorporate both individual and social factors that may affect outcomes, such as self-efficacy, attitude, or social support (Owen et al., 2004). Neighborhood level factors of safety and deprivation may confound the effect of green space on physical activity, and should be considered in future research. While our study focused on adults of mostly Dutch origin, the inclusion of youth and non-Dutch residents would offer a more representative group of green space users. Objective measures of walking and cycling, through the use of accelerometers or GPS trackers, might strengthen the validity of

outcome values. Additional green space indicators, such as network distance, can be used to better evaluate the use of green space, reflecting likely routes of access. Similarly, the number of green spaces present within a residential area, and a specification of the types of changes occurring in green space, may provide a more robust analysis. Testing for interaction would assess the cumulative effects that multiple factors may have on physical activity. Finally, conducting similar studies in diverse geographic settings on large study samples would help build a solid foundation of evidence generalizable to a wider population.

5. Conclusions

The methods used to study relationships between place and health greatly shape the foundation of knowledge that exists in this field. Our approach separately compared group-level associations, and individual within-person effects, of green space on walking and cycling, leveraging longitudinal data to strengthen the basis for causal inference. Our results indicate that walking, and particularly leisure walking, decreases as green spaces are moved further from one's residence. However, local green space alone may not significantly affect physical activity. Replicating our approach on larger, diverse study samples with more variability across time would strengthen the reliability of these findings, or introduce different patterns of effect. Future research should aim to identify aspects of the quality and quantity of changes required in the built environment to improve physical activity, which can steer urban planning and policy efforts and ultimately guide the prevention of chronic disease in an increasingly urbanized world.

Ethics approval and consent to participate

The use of personal data in the GLOBE study is in compliance with the Dutch Personal Data Protection Act and the Municipal Database Act, and has been registered with the Dutch Data Protection Authority (number 1248943).

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated during and/or analysed during the current study are not publicly available due to privacy regulations but are available from the corresponding author on reasonable request.

Declaration of competing interest

The authors declare that they have no competing interests.

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