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Visualizing changes in physical activity behavioral patterns after redesigning urban infrastructure

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ABSTRACT

The aim of this study was to explore effects of a major urban reconstruction on physical activity (PA) behavior by comparing PA intensity hotspots before and after the tunneling of a highway with a new infrastructure prioritized for walking and cycling. In total, 126 individuals participated before and after the tunneling. GPS loggers and accelerometers were used to assess location and PA levels. A geographic information system (GIS) was used to perform optimized hotspot analyses on PA data, both on transport and stationary data points. The results showed several changes in PA hotspots on trip data, even if total PA levels did not change. At follow-up, PA intensity hotspots were more connected, with the new infrastructure as a central connection. This was true for higher and lower educated individuals. Therefore, if changes in the built environment do not result in changes on population-level outcomes, this does not imply that they have no impact on behavior.

1. Introduction

About half of the world's population currently lives in urban areas, with estimates showing that this number will increase by up to 70% by 2050 (United Nations, 2019). This increased urbanization is associated with several threats to public health, such as an increase in motorized traffic, air pollution, noise pollution, and a lack of green space (Nieuwenhuijsen, 2016). This has serious consequences for the livability of cities. In 2015, the United Nations (UN) presented their Sustainable Development Goals, one of which is to make cities and human settlements inclusive, safe, resilient, and sustainable. As well as ensuring adequate housing for everyone, it aims to provide access to safe, affordable, accessible, and sustainable transport systems, universal access to safe, inclusive, and accessible green and public spaces, and to reduce the adverse per capita environmental impact of cities (United Nations, 2015). This UN goal underlines the role of the built environment in population health and wellbeing. By definition, the built environment includes places and spaces created or modified by people including buildings, parks, and transportation systems (Transportation Research Board and Institute of Medicine, 2005). The availability of trails and community gardens, and walkability and bike ability are mentioned as health assets of the built environment (Lee et al., 2008).

The relevance of the built environment as a determinant of population health is expressed by multiple socioecological frameworks (Schulz and Northridge, 2004; Sallis et al., 2015). The built environment can affect health and wellbeing via several factors, such as neighborhood and housing conditions, safety (from traffic and crime), and toxins (Schulz and Northridge, 2004). But social aspects such as social cohesion and participation also play a role. Lastly, the built environment can act as a facilitator for health behaviors such as physical activity and active transport (Kremers et al., 2006). In recent years, numerous cities worldwide have invested in their built environment to increase physical activity and active transport of their inhabitants, for example by adding walking and cycling routes, rail-to-trail conversions, or improvements to parks and green space (Hunter et al., 2015; Ogilvie et al., 2011; Troped et al., 2001).

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Existing research assessing the effects of the built environment on health behaviors mainly focused on overall physical activity levels and the levels of active transport. Systematic reviews synthesizing the results of these evaluations found positive relationships between changes in the environment and physical activity, especially for active transport. However, the results show inconsistencies in the direction and magnitude of outcomes due to differences in context and measuring method (Mayne et al., 2015; Stappers et al., 2018a; Mölenberg et al., 2019). Also, personal factors such as sociodemographics, personality and physiological factors may moderate the relationship between environment and behavior (Kremers et al., 2006; Lakerveld et al., 2012), which means that the effect of the environment on behavior might be different for certain subgroups in society. This implies that in evaluations, overall intervention effects might be canceled out due to subgroup differences. A review assessing the effects of changes in the built environment on physical activity and diet found that in some cases projects did not achieve intended outcomes on the total sample, but when stratified for SES or migrant status, developments were found to minimize gaps in health inequity (MacMillan et al., 2018). These subgroup differences were also found in a review on the differences between males and females when it comes to effects of the built environment on physical activity (Tcymbal et al., 2020). In addition, Smith and colleagues found some indications that improvements in infrastructure might predominantly benefit socioeconomically advantaged groups (Smith et al., 2017). A cross-sectional study by Wali et al. (2022) showed that a new light rail line in Portland did not result in an average increase of physical activity, but substantial heterogeneity was observed for subgroups, both in the direction and magnitude of behavioral change (Wali et al., 2022). More and longitudinal research is needed to investigate whether non-significant changes in behavior after a built environment or infrastructural change is reflecting reality, or whether subgroup differences are present but overall changes are canceled out. Therefore, we will include stratified analyses to investigate possible subgroup effects.

Next to these methodological considerations, it is important to explore subgroup differences because individuals with a lower socioeconomic position might be more vulnerable to environmental exposures such as noise and air pollution as they live more frequently in or around environmental hazards such as main roads (Hoffmann et al., 2003). Living close to main roads has a detrimental effect on the health outcomes, especially for individuals that are already vulnerable and have chronic conditions. For these individuals, living next to a main road may increase existing health inequalities and lead to even poorer health outcomes (Foley et al., 2017). Therefore, more research is needed to study whether improvements in the built environment might be distributed unequally among the population.

Besides presenting whether a change in the built environment was able to increase the total amount of (transport-based) physical activity, the context-sensitivity of this issue warrants also focusing on *how* it works (Panter et al., 2019). Besides focusing on overall physical activity outcome measures, it is also relevant to study how behavioral patterns change as a result of changes in the built environment. Especially in studies that evaluate large infrastructural projects, changes in behavior are more often small or non-significant in comparison to smaller interventions (Stappers et al., 2018a). More extensive interventions typically imply major changes to the entire system (Rutter et al., 2017). Large changes in the system might eventually lead to changes in physical activity and active transport, but also to compensatory adaptive processes and feedback loops that make it harder to assess clear mechanistic pathways and direct effects (Hamid, 2009). However, this does not mean that travel behavior of the users of large infrastructural changes is not changing. Geospatial analysis can provide in-depth information about the use of a specific area before and after a change to the built environment, by contextualizing the results. It can complement existing evaluation research by exploring whether a change in the function of an area leads to a different use of that specific area. It can inform policy makers and urban planners about the effects of redesigned environments on the behavior of the inhabitants and users of the area, even before evaluations identify changes in overall physical activity levels. One specific form of geospatial analysis, (Optimized) Hot Spot Analysis, has been used in previous research to investigate behavioral patterns in parks and schoolyards. This was able to reveal where individuals are actually active and how active they are, relative to the total amount of physical activity in the entire area (Andersen et al., 2019; Clevenger et al., 2019). Thus far, this technique has not been used to explore changes in behavioral patterns in large infrastructural projects.

A crosstown highway was tunneled in the city of Maastricht, The Netherlands. On top of this tunnel, new infrastructure was created aiming to stimulate PA by prioritizing pedestrians and bicyclists, the so-called Green Carpet. After a year, the effect evaluation showed that physical activity and active transport levels increased significantly on the Green Carpet, but that the total amount of physical activity or active transport in the neighborhood where the participants lived did not change (Stappers et al., 2021). The aim of the current study was to explore possible effects of an urban reconstruction on physical activity behavioral patterns of area users and nearby residents. We did this by comparing physical activity intensity hot spots before and after the reconstructions. In addition, we investigated whether changes in hot and cold spots were different for individuals with a lower or higher socioeconomic position, and tested whether sociodemographic characteristics were associated with the use of the Green Carpet. Eventually, we tested associations between the use of the Green Carpet and physical activity outcomes.

2. Methods

2.1. The Green Carpet

Since the 1950s, the city of Maastricht, The Netherlands, has had a major highway (A2/N2) running through it, resulting in both a physical and a social barrier between deprived neighborhoods in the east of the city. In 2016, a double-layered tunnel was opened to facilitate long-distance motorized traffic. On top of this tunnel, a wide semi-paved section in the middle has been prioritized for use by pedestrians, cyclists and for recreation. Two one-way streets were created to accommodate the remaining local traffic. The middle section is separated from the adjacent streets by wide strips of grass and trees, creating the so-called 'Green Carpet' (www.mijngroeneloper.nl). Although the Green Carpet has officially been in use since 2018, construction of houses and facilities in the area is still ongoing and will continue until 2026. More details about the context of this project are described elsewhere (Stappers et al., 2020). Images pre- and post-reconstruction are available in appendix 1.

2.2. Design and participants

The data in this article are a subsample of a larger study, evaluating the effects on physical activity and health of tunneling a highway with a physical activity-friendly environment on top of this tunnel (Stappers et al., 2021). For the current analyses, we used the data of individuals living in East Maastricht (Fig. 1; black outline), that visited the reconstructed area (Fig. 1; dashed outline) during the period in which the measurements were taken. The reconstructed area covers the Green Carpet (tunnel and new infrastructure on top of it), newly built and existing connections to the Green Carpet, the redesigned public space, and the planned real estate areas adjacent to the new public space that were presented in the master plan. Baseline measurements were performed between August 2016 and July 2017. Follow-up measurements took place between August 2018 and July 2019, in the same month of the year as the baseline measurement, to limit the effect of daylight and seasonality on the results. Only participants that provided valid data on both time points were selected for the analyses. Participants that moved between baseline and follow-up were excluded.

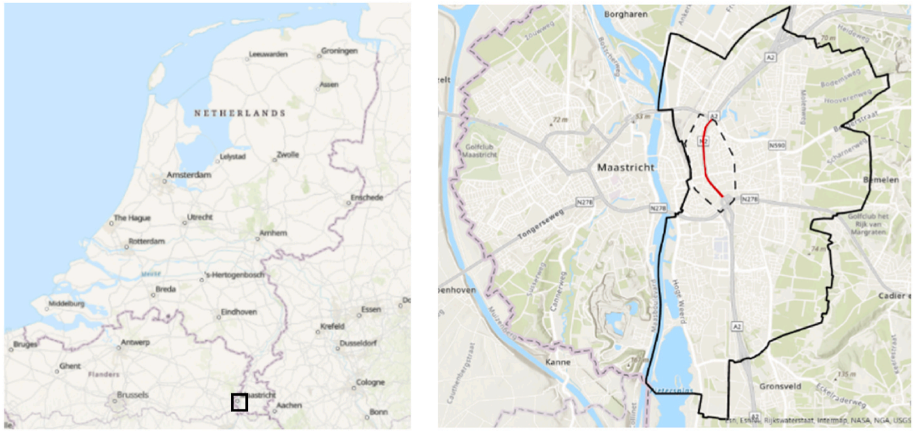

Fig. 1. Left: Location of the city of Maastricht, in the south of The Netherlands; Right: East Maastricht area in black, with reconstructed area in dashed line and in red the highway section that was tunneled.

Participants were recruited through social media, posters, flyers at supermarkets and local events, advertisements in local and regional newspapers, and via personalized mailings to a random sample of 10,000 inhabitants (total population 31,457). Individuals that were interested in participating received an information letter and provided written informed consent before taking part in the study. The study protocol was reviewed by the medical ethical committee of the Maastricht University Medical Center + (MUMC+), who judged that formal ethical approval was not required (METC 16-4-109). The study was registered at the Netherlands Trial Register (NL8108).

2.3. Data collection

Physical activity and location data were collected using a Qstarz BT-Q1000XT GPS logger (Qstarz International Company, Taipei, Taiwan) and an Actigraph GT3X + accelerometer (Actigraph, Pensacola, FL, USA), which were worn for 6 days in an elastic belt, placed at the right hip. The devices were removed at night and during activities that involved water, such as swimming and showering. The GPS device was charged overnight using the accompanying charger.

All participants completed a questionnaire about their socio-demographics, including age, gender (0 = male, 1 = female), educational level (recoded into 0 = lower educated, for individuals with secondary vocational education or less, and 1 = higher educated, for individuals with higher professional education or higher), work status (recoded into 0 = not working, 1 = working), and car ownership (0 = no car in household, 1 = at least one car in household). SPSS version 24.0.0.2 (IBM Corp., Armonk, NY, USA) for all statistical and descriptive analyses in this paper.

2.4. Data analysis

Accelerometer and GPS logger data were combined using HABITUS. Accelerometry and GPS data were merged into 60-s epochs, filtered and processed using the Human Activity Behavior Identification Tool and data Unification System (HABITUS).

Invalid GPS data points were identified based on extreme changes in speed (>130 km/h) and elevation (1000m) between two epochs. Data points were distinguished as 'stationary' points (staying in one location, defined as less than 100m of displacement within 120 s), and points that were part of a trip. A datapoint was classified as part of a trip if the distance traveled between consecutive datapoints was at least 100 m and the duration exceeded 120 s. A stop of at least 120 s at one location was marked as a pause point and a pause of more than 180 s was marked as the endpoint of a trip. Periods of at least 60 min of zeros were classified as non-wear time and excluded from the analyses. The trip detection algorithm had an accuracy of 92.5%, a sensitivity of 88.5%, specificity of 93.4%, a positive predictive value of 74.9% and a negative predictive value of 97.3% (Carlson et al., 2015). The actual use of the Green Carpet was determined by combined GPS and accelerometer data and coded into 1 (used the Green Carpet during the measurements) or 0 (did not use the Green Carpet).

2.5. Total and trip-based physical activity levels

To calculate total and trip-based physical activity levels, Freedson's cut points (1998) were applied to distinguish sedentary behavior (SB; <100 counts per minute) and light physical activity (LPA; 100–1952 activity counts per minute), moderate-to-vigorous physical activity (MVPA; >1952- counts per minute) (Freedson et al., 1998). Outcome measures for the total and trip-based physical activity levels were the percentage of SB, LPA and MVPA per day, and the percentage of SB, LPA and MVPA of the total time spent in transport. In addition, paired-samples T-tests were performed to explore differences in PA levels between baseline and follow-up, using a p-value of .05 as threshold for significance.

2.6. Optimized hot spot analysis

A geographic information system (GIS) (ArcGIS Pro 2.7.1, Environmental Systems Research Institute, 2017, Redlands, CA: Environmental Systems Research Institute) was used for geospatial data selection, analyses, and visualization of the results. First, all combined GPS and accelerometer data of the inhabitants of East Maastricht were added to ArcGIS Pro (Fig. 2). Second, we selected data within the specific Green Carpet area (Fig. 1 – right) for valid days (>8 h of wear time) for participants that provided at least five valid days of data. Next, data were filtered to exclude time at home and/or work as these are not public spaces.

Each data point contained a trip classification and was classified as a stationary data point or trip data point. The dataset was sorted on the trip classification to be able to run optimized hot spot analyses for stationary data points and trip data points separately. The trip datapoints are all individual datapoints that provided data on physical activity intensity (counts per minute) and location during transport, while the stationary data points provided data on the physical activity intensity at one specific location.

The optimized hot spot analysis function in ArcGIS Pro was used to identify spatial clusters, which are locations where the physical activity intensity (counts per minute) of the participants was significantly higher or lower, compared to other locations in the area. The optimized hot spot analysis automatically derives parameters for analyses (i.e. distance

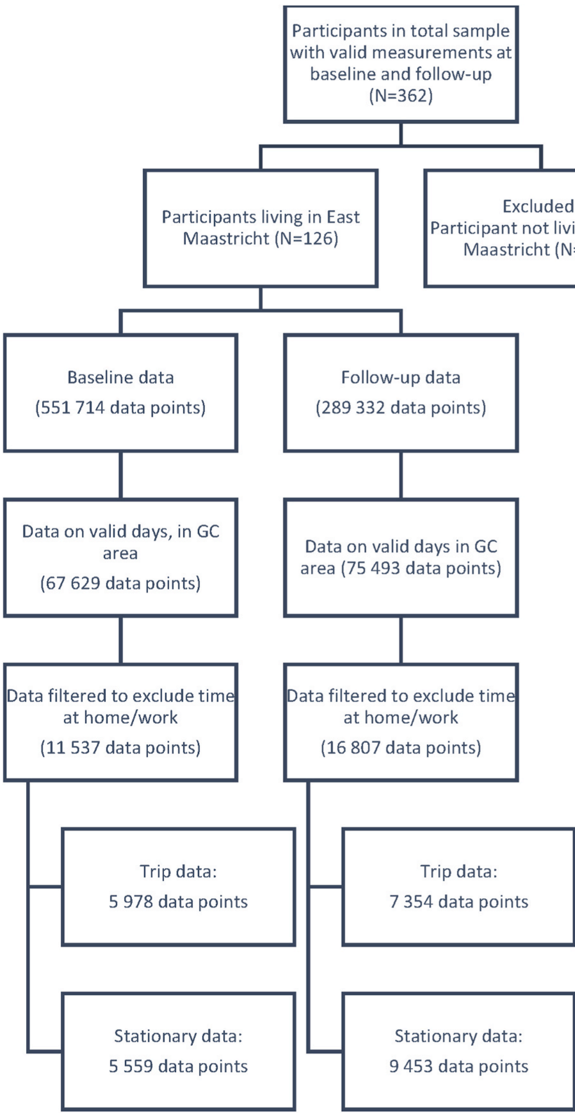

Fig. 2. Flowchart data inclusion; GC = Green Carpet.

band and number of neighbors) from the input data. Additionally, it adjusts for multiple testing and spatial dependence using the False Discovery Rate correction method (Environmental Systems Research Institute, 2017). In the current analyses of the trip data, the optimal fixed distance band was based on the average distance to 30 closest neighbors and was 38 m and 39 m for baseline and follow-up, respectively. For the analyses of the stationary data, this was 20 m for both baseline and follow-up. For each data point, the tool calculates a Z-score and p-value, based on the physical activity intensity score. Data points with a relatively high Z-score that are surrounded by other points with high Z-scores will be marked as a significant hot spot when the observed local sum of the physical activity intensity of that point and its neighbors is significantly higher than expected. By contrast, cold spots were marked when the observed local sum of the physical activity intensity of a certain point and its neighbors was significantly lower than expected. Significant p-values for hot spots and cold spots are visualized using three levels of confidence: 90% confidence, 95% confidence, and 99% confidence. Hot spots and cold spots were provided for stationary data and trip data separately. In addition, sensitivity analyses were performed to explore the changes in hot and cold spots for subgroups based on educational level.

2.7. Regression analyses

Regression analyses were conducted to statistically test the associations between sociodemographic characteristics and the use of the Green Carpet, and transport-based and total physical activity. First, logistic regression was used to examine the associations between sociodemographic characteristics (age, gender, educational level, work status and car-ownership) and the use of the Green Carpet at follow-up. We controlled for the use of the Green Carpet at baseline, as participants could have used the highway (e.g. in transit or by crossing) before it was tunneled. All variables were inserted in the analyses using the enter method.

Second, multivariate linear regression analyses were conducted to assess the association between the use of the Green Carpet at follow-up and transport-based and total physical activity levels (SB, LPA, MVPA), while controlling for the use of the Green Carpet at baseline, and sociodemographic characteristics. Lastly, interaction terms were calculated for possible interactions between sociodemographic characteristics and the use of the Green Carpet at follow-up. These interactions were added in a separate block to the multivariate linear regression model described above. A p-value of .10 was used for the interaction terms (Stone-Romero and Liakhovitski, 2002) and stratified analyses were performed to visualize the significant interactions.

3. Results

3.1. Participant characteristics

In total, 126 individuals provided valid data at both baseline and follow-up. At baseline, the mean age of the participants was 55.9 (14.1) years. In total, about 58% were female, 56% higher educated and 56% employed (see Table 1).

Of the participants, 62.7% and 65.1% used the Green Carpet at baseline and follow-up, respectively. Subgroup analyses on lower and higher educated individuals showed similar values for the use of the Green Carpet. Total physical activity and transport-based physical activity levels did not significantly change over time, neither for the total sample nor for subgroups based on educational level (Table 2). At baseline, the percentage transport-based MVPA was significantly higher in lower educated individuals than in higher educated individuals.

3.2. Hot and cold spot analyses trip data

First, only data points that were part of a trip were included in the hot spot analyses (Fig. 3). At baseline, relatively small hot spots were found on various routes, indicating that trips on these streets had a significantly higher physical activity intensity. On the east side of the former highway, a larger hot spot was found at a small shopping center and a connecting street (S). This is an important connection (C) to an area north of the reconstructed area, which houses sports facilities and a park. On the west side of the former highway, a significant hot spot was found at the railway station (R). Also, in the south of this area, significant hot spots highlighted the most important connections to an area south of this reconstructed area, housing the university health campus and the academic hospital (U). Significant cold spots were mainly concentrated on the former highway (H) and at major roads, indicating

Table 1
Baseline characteristics of participants.

Sociodemographic characteristic (N = 126)	Baseline Mean (SD)/%
Age (Mean (SD))	55.9 (14.1)
Gender (%male)	57.9
Educational level (% higher educated)	56.3
Work status (% employed)	56.9
Car ownership (% ≥1 car in household)	86.5

Table 2
Physical activity levels of total sample and subgroups based on educational level at baseline and follow-up, and results of T-tests.

	Total sample (N = 126)		*p*	Lower educated (N = 55)		*p*	Higher educated (N = 71)		*p*
	Baseline	Follow-up		Baseline	Follow-up		Baseline	Follow-up	
Users Green Carpet	62.7%	65.1%		60.0%	65.5%		64.8%	64.8%	
Total physical activity									
SB (% of the day)	64.08 (8.47)	64.89 (8.46)	0.141	60.91 (8.06)	62.02 (8.32)	0.223	66.53 (8.01)	67.09 (7.69)	0.394
LPA (% of the day)	31.54 (7.76)	31.04 (7.85)	0.376	34.50 (7.20)	33.70 (29.26)	0.360	29.26 (7.45)	29.02 (7.57)	0.727
MVPA (% of the day)	4.38 (2.92)	4.07 (2.83)	0.138	4.59 (3.10)	4.28 (2.85)	0.413	4.22 (2.78)	3.89 (2.78)	0.209
Transport-based physical activity									
Transport-based SB (% of all transport)	49.74 (15.01)	49.91 (14.62)	0.904	44.54 (14.47)	46.67 (12.12)	0.152	53.87 (14.26)	52.40 (15.57)	0.440
Transport-based LPA (% of all transport)	33.78 (10.72)	34.67 (10.25)	0.387	36.71 (10.33)	36.61 (10.33)	0.912	31.50 (10.31)	33.36 (10.75)	0.217
Transport-based MVPA (% of all transport)	16.47 (12.37)	15.41 (11.73)	0.303	18.76 (14.11)[a]	16.72 (11.66)	0.137	14.64 (10.84)	14.24 (11.51)	0.935

[a] = significantly different from transport-based MVPA in higher educated individuals at baseline, p = .029.

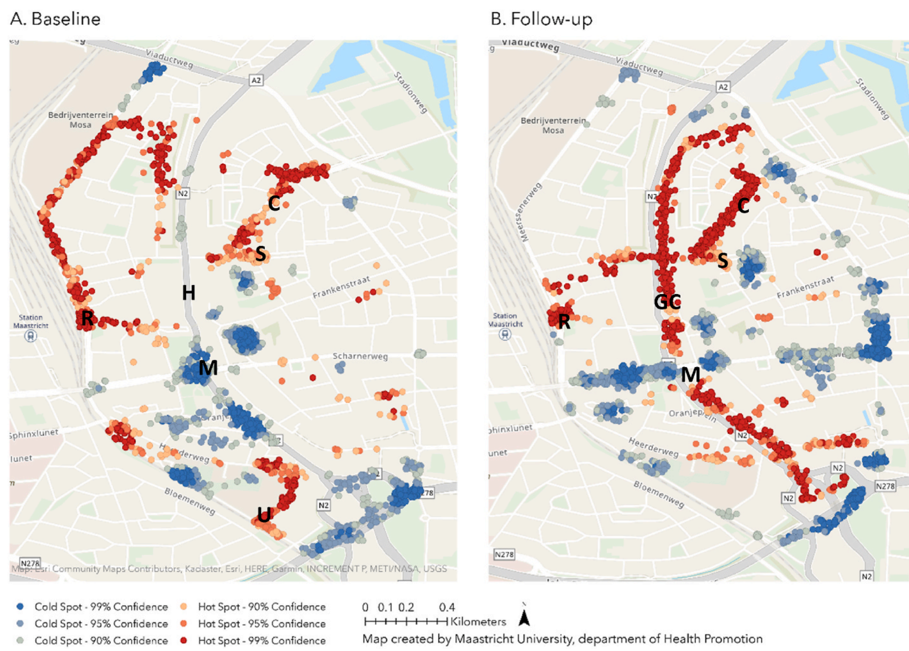

Fig. 3. Results of optimized hot spot analysis – trip data; C = connecting street between shopping center and sports facilities/park; S = shopping center; H = former highway; M = horizontal street; GC = Green Carpet; U = connection to university/hospital.

that trips on these streets had a significantly lower physical activity intensity.

At follow-up, hot spots throughout the area were more connected compared to the baseline measurements. The larger hot spot on the east side of the former highway that was found at baseline was still present at follow-up.

In addition, hot spots were found along the entire Green Carpet (GC; image in Supplementary Fig. S1b), except for the section where a major street intersects the area (somewhere in the middle of the reconstructed area; M). Also, we found significant hot spots at two east-west connections, indicating that participants used an active form of transport not only along the Green Carpet on the north-south connection, but also for east-west movements. Comparable to baseline, cold spots were mainly found on major roads. However, while cold spots on the Green Carpet diminished, new cold spots were found along a road parallel to the Green Carpet (P), indicating a possible new connection for passive transport.

3.3. Hot and cold spot analysis of stationary data

In the analyses of the stationary data, only data points that were collected while the participant was at one specific location (less than 100m of displacement within 120 s) were included in the hot spot analyses.

At both baseline and follow-up, two similar hot spots were present on the east side of the highway/Green Carpet (Fig. 4). Both activity hot spots are at a location with a concentration of supermarkets and shops (S). Further, one activity cold spot was found at a community center (CC) meaning that individuals were significantly less active in this spot compared to other places in the area. Other cold spots were not accessible for the public (i.e. private houses). We observed hardly any significant stationary activity hot spots or cold spots along the Green Carpet, which means that the Green Carpet is not a destination in terms of physical activity or active or passive recreation.

3.4. Sensitivity analyses based on educational level

To explore possible differences in results between individuals with a lower or higher educational level, hot spot analyses were performed for both groups. For the trip data, the hot spots of lower educated individuals were mainly present on the north side of the reconstructed area (Supplementary material, Fig. S1). Although the hot spots at a shopping center (S) and connecting street (C) did not change, the Green Carpet became a large hot spot at follow-up. For higher educated individuals, hot spots were concentrated in the south of the reconstructed area at baseline. This was as expected as more social housing is located in the northern part, while more privately owned and more expensive

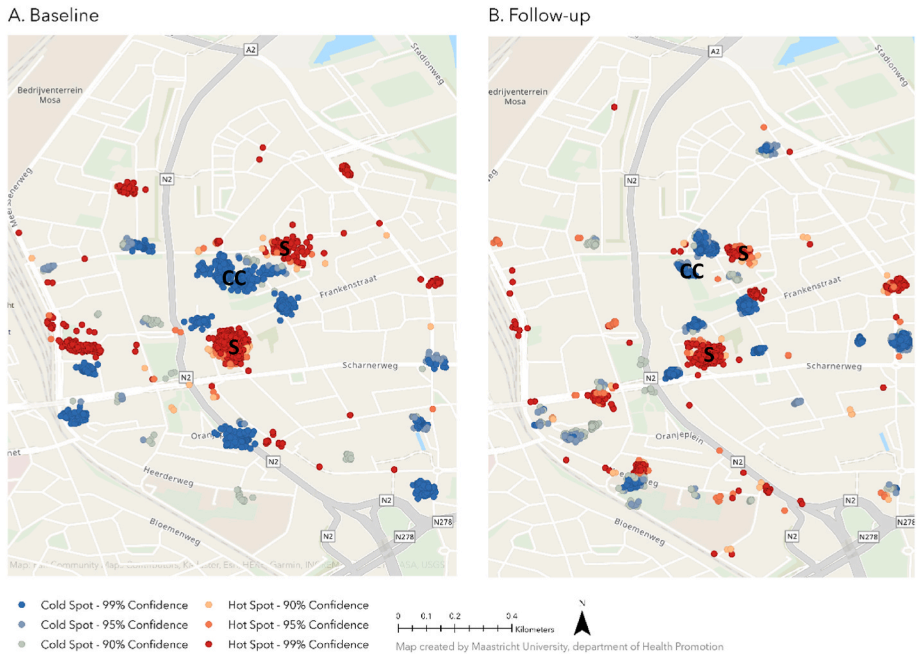

Fig. 4. Results of optimized hot spot analysis – stationary data. S = shopping center; CC = community center.

houses are situated on the south side. However, for higher educated individuals too, the Green Carpet became a large hot spot at follow-up. This implies that the Green Carpet attracts individuals from different areas, with both lower and higher educational attainment.

Sensitivity analyses for stationary data showed hot and cold spots similar to group-level data. No specific patterns were observed.

3.5. Associations between sociodemographic characteristics and behavior

Only car-ownership was associated with the use of the Green Carpet at follow-up, when controlling for the use of the Green Carpet at baseline (B = −1.647; p = .041), but it was not associated with transport-based or total physical activity levels. None of the other sociodemographic characteristics were significantly associated with the use of the Green Carpet at follow-up, which validates the findings of the hot spot analyses that the Green Carpet attracts individuals with both lower and higher educational attainment. Further, the use of the Green Carpet at follow-up was associated with less transport-based SB at follow-up (β = −.231; p = .016), but not with transport-based LPA or MVPA (Table 3). For transport-based SB and transport-based MVPA, a significant interaction was found for the use of the Green Carpet at follow-up and educational level (SB: β = 0.366, p = .081; MVPA: β = −0.453, p = .037). Stratification analyses showed that for lower educated individuals, the use of the Green Carpet at follow-up was significantly associated with less transport-based SB at follow-up (β = −.430, p = .001), when controlling for the use of the Green Carpet at baseline and sociodemographic characteristics. For higher educated individuals, no significant association was found (Fig. 5). Similarly, the use of the Green Carpet was significantly associated with more transport-based physical activity in lower individuals (β = 0.339, p = .026), but not for higher educated individuals.

For total physical activity levels, the use of the Green Carpet was

Table 3
Associations between the use of the Green Carpet and transport-based physical activity levels.

	% transport-based SB[a]				% Transport-based LPA[a]				% Transport-based MVPA[a]			
	Model 1		Model 2		Model 1		Model 2		Model 1		Model 2	
Sociodemographic characteristics	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*
Age	.039	.740	.021	.915	−.105	.391	−.297	.148	.043	.721	.237	.241
Gender	−.090	.340	−1.707	.091	.021	.831	.127	.477	.095	.327	.256	.150
Work status	−.074	.516	−.301	.764	.041	.729	−.163	.439	.057	.625	.220	.289
Educational level	.188	.053	−.300	.765	−.191	.057	−.205	.265	−.068	.492	.247	.172
Car ownership	.119	.228	1.157	.250	−.028	.781	−.058	.583	−.125	.219	−.096	.358
Explained variance R2	.094		.094		.055		.055		.067		.067	
Use of Green Carpet	**−.231**	**.016**	−.822	.413	.163	.099	−.512	.425	.148	.132	1.088	.087
Explained variance R2	.142		.142		.079		.079		.087		.087	
Interactions												
Use of GC x work status			−.055	.822			.314	.220			−.208	.408
Use of GC x educational level			**.366**	**.081**			−.011	.961			**−.453**	**.037**
Use of GC x car ownership			[b]				[b]				[b]	
Use of GC x age			−.070	.888			.669	.199			−.504	.326
Use of GC x gender			.319	.125			−.172	.428			−.252	.240
Explained variance			.186				.109				.133	

GC = Green Carpet; SB= Sedentary behavior; LPA = light physical activity; MVPA = moderate-to-vigorous physical activity; β = standardized beta; p = statistical significance.

[a] Corrected for use of the Green Carpet at baseline.

[b] = excluded from regression analyses.

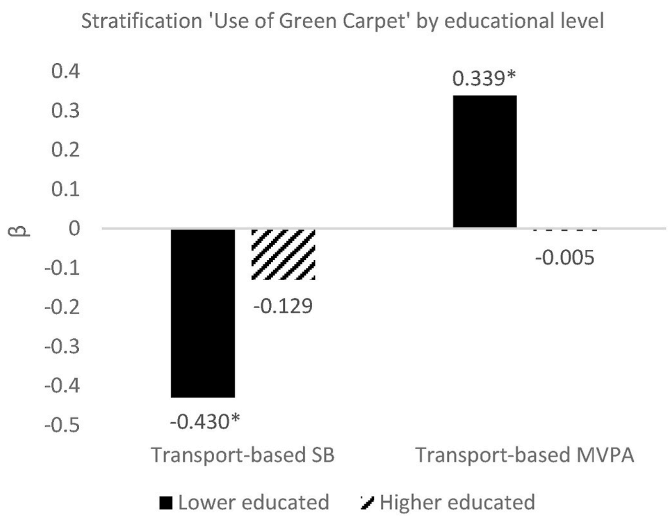

Fig. 5. Interactions between educational level and the use of the Green Carpet at follow-up, for transport-based SB and MVPA; * = p < .05.

associated with less LPA (β = −1.599, p = .024) and significant interactions were found between use of the Green Carpet at follow-up and age (Table 4). However, stratified analyses of the significant interactions showed no significant associations between the use of the Green Carpet and total SB and LPA when stratifying on the median age of the sample. For total percentage MVPA per day, a significant interaction between the use of the Green Carpet and educational level was found (β-.416, p = .040), and stratified analyses showed that for lower educated individuals, the use of the Green Carpet at follow-up was associated with more total MVPA (β = 0.349, p < .005), while for higher educated individuals no significant association was found.

4. Discussion

The aim of this study was to explore possible effects of a major urban reconstruction on physical activity behavioral patterns by comparing hot and cold spots before and after the reconstruction. In addition, we investigated whether changes in hot and cold spots were different for individuals with a lower or higher educational attainment. Even though total and transport-based physical activity levels did not change for the total sample nor the subgroups, the results show clear changes in the physical activity behavioral patterns in the total sample and in both higher and lower educated inhabitants. Interactions between educational level and the use of the Green Carpet at follow-up were found and stratified analyses showed that using the Green Carpet was associated with less transport-based SB and more transport-based MVPA in lower educated individuals, but not for higher educated individuals. In addition, the use of the Green Carpet was also associated with a higher percentage MVPA per day, but only in lower educated individuals as well. This indicates that even though educational level did not predict the use of the Green Carpet, the use of the Green Carpet by lower educated individuals is associated with decreased transport-based SB and increased transport-based and total percentage of MVPA per day. This is in contrast to the suggestion of Smith et al. who suggested that socioeconomically advantaged groups might benefit the most from improvements in the built environment (Smith et al., 2017). A possible explanation could be the centration of neighborhoods with a low socioeconomic status near the former highway. The walkability and connectivity of these neighborhoods drastically improved after tunneling the highway and creating the Green Carpet, and living in a high-walkable neighborhood is found to be associated with more MVPA and walking and bicycling for transport (Van Dyck et al., 2010). The higher SES neighborhoods are situated further away from the new infrastructure, so possibly the walkability of these neighborhoods was already higher, which is in line with previous research that found that more educated neighborhoods are also more walkable (King and Clarke, 2015). This could cause a ceiling effect in the relationship between walkability and physical activity in these neighborhoods, meaning that their physical activity levels are less likely to change. However, other research found contrasting results indicating that census sections with higher socioeconomic status had a lower walkability score (Gullón et al., 2017). In addition, the subgroup differences might result in non-significant associations for the total sample, but more research is needed to further understand the differences between subgroups in society.

The new infrastructure led to changes in the physical activity intensity hot spots in the reconstructed area, especially for trip data. At follow-up, hot spots were more connected compared to baseline, with the Green Carpet being a central connection. Thus, the results show that the urban reconstruction prioritized for pedestrians and bicyclists has led to increased use of this infrastructure for active transport, both as a connection from north to south and as a connection between neighborhoods east and west of the former highway. This is in line with previous research, that found that a better street connectivity was

Table 4
Associations between the use of the Green Carpet and total physical activity levels.

	% SB[a]				% LPA[a]				% MVPA[a]			
	Model 1		*Model 2*		*Model 1*		*Model 2*		Model 1		Model 2	
Sociodemographic characteristics	β	*p*	β	*p*	β	*p*	β	*p*	β	p	β	p
Age	.176	.113	.464	.014	−.197	.077	**−.585**	**.002**	.166	.868	.237	.223
Gender	**−.199**	**.030**	−.122	.442	**.205**	**.025**	.059	.710	.284	.777	.201	.225
Work status	−.102	.349	−.045	.810	.042	.702	−.145	.436	.190	.097	.537	.006
Educational level	**.337**	**.000**	.158	.327	**−.337**	**.000**	−.245	.130	−.072	.461	.208	.215
Car ownership	.010	.913	.348	.154	.046	.611	−.231	.344	−.159	.099	−.402	.115
Explained variance R^2	.188		.188		.190		.190		.098		.098	
Use of Green Carpet	−.028	.751	1.151	.101	−.008	.930	**−1.599**	**.024**	.105	.257	.997	.173
Explained variance R^2	.189		.189		.190		.190		.109		.109	
Interactions												
Use of GC x work status			−.094	.677			.290	.203			−.524	.028
Use of GC x educational level			.279	.148			−.151	.432			**−.416**	**.040**
Use of GC x car ownership			−.479	.195			.346	.349			.474	.218
Use of GC x age			**−.916**	**.057**			**1.243**	**.010**			−.711	.155
Use of GC x gender			−.048	.801			.152	.427			−.280	.163
Explained variance R^2			.263				.261				.198	

GC = Green Carpet; SB= Sedentary behavior; LPA = light physical activity; MVPA = moderate-to-vigorous physical activity; β = standardized beta; p = statistical significance.
[a] Corrected for use of the Green Carpet at baseline.

associated with the use of active transport (Koohsari et al., 2014; Oakes et al., 2007). Also, the reconstructed area is not only a facilitator for north-south movements, but some east-west connections are starting to emerge as well. With the new infrastructure, local destinations might be more accessible for inhabitants, leading to more walking trips (Pikora et al., 2003).

Although physical activity behavioral patterns changed over time, the volume, i.e. the amount of physical activity did not increase, neither on a population level nor in subgroups based on educational level. Especially for higher educated individuals, of which the use of the Green Carpet was not associated with more transport-based physical activity, our analysis suggests that trip-based physical activity might have been rerouted and centralized from streets adjacent to the Green Carpet. This is also seen in other evaluations of changes in active transport routes in Europe (Vasilev et al., 2018). For example, it is known that the amount of traffic and the quality of paths (Chang, 2020) can influence route choice for active transport. The Green Carpet is a path with several qualities (e.g. wide and comfortable path, surrounded by green areas) and is separated from motorized traffic. Also, the tunneling of the highway has led to a noise reduction and a decrease in nitrogen and particulate matter (Atlas Living Environment, 2019). Consequently, the new infrastructure might attract pedestrians and cyclists who used to travel on less attractive roads at baseline.

Furthermore, it could be the case that the participants in this study are still at an early stage of behavioral change (Prochaska and DiClemente, 2005). The results show that individuals are aware of the new route and have started to use the infrastructure, even though it has not yet led to additional physical activity. This behavioral change might influence other behaviors and forms of transport in individuals' daily lives, resulting in more physical activity in the long term. Some reviews have shown that it might take up to 6–12 months before actual behavioral change on total or transport-based physical activity levels is measurable (Mayne et al., 2015; Stappers et al., 2018a). More recent research suggests that it might take even more than three years to detect behavioral change after large-scale infrastructural interventions (Wali et al., 2022).

Also, the increase in physical activity on the Green Carpet might be compensated by decreased physical activity levels in another domain, as described by the ActivityStat hypothesis (Gomersall et al., 2013; Rowland, 1998). The ActivityStat hypothesis proposes that an increase in physical activity in one domain, will be compensated in another domain, to maintain a stable level of physical activity (Rowland, 1998). However, the existence of such ActivityStat is the subject of debate among researchers and clear evidence is lacking (Gomersall et al., 2013). A longer-term follow-up is needed to explore whether these changes in the physical activity pattern will lead to changes in physical activity during the day in the long term.

Hot spot analyses on the stationary data points showed no clear change in the locations of hot and cold spots, before and after the opening of the Green Carpet. As shown in previous research, moderate-to-vigorous physical activity in the public space is associated with the presence of certain features and destinations in the environment, such as green space, residential areas, shops, sports terrains and other facilities (Jansen et al., 2016; Koohsari et al., 2014). This is in line with the findings of our study, as shops and local shopping areas were one of the few hot spots for stationary data points. For parks specifically, user facilities such as gym equipment, coffee bars and public toilets are most likely to attract visitors (Grilli et al., 2020). At the time of the follow-up measurement, only the new infrastructure of the Green Carpet was in use, and recreational and residential areas were still in development. The lack of facilities or destinations for physical activity might be a reason for the absence of hot spots in stationary data along the Green Carpet.

While the former highway accommodated mostly motorized traffic passing by the city, the analyses showed that the Green Carpet area is also used by residents of the neighborhoods bordering this area. This means that the Green Carpet is not only a transit route, but also provides greater connectivity for the inhabitants living there. Sensitivity analyses showed that the new infrastructure turned into a physical activity intensity hot spot for both lower and higher educated inhabitants. Previous research showed that predictors of use of new infrastructure included a better general health and higher education or income (Goodman et al., 2013). However, our analyses showed that educational level nor work status was a significant predictor for the use of the Green Carpet. This can be explained by the different layers of the hierarchy of walking needs that have been influenced by the large infrastructural changes (Alfonzo, 2005). Previous research has shown that for less well-off individuals, the lower order needs (i.e. feasibility, accessibility and safety) were associated with physical activity, while for more well-off individuals, higher order needs such as comfort and pleasurability were more important (Stappers et al., 2018b). This implies that different subgroups in society might have different facilitators for physical activity. The current study shows that an integrative approach focusing on fundamental needs such as safety and accessibility, as well as comfort and aesthetics, is able to attract both lower and higher educated individuals.

In light of the Sustainable Development Goals, apart from the effects on physical activity patterns through better and green connectivity, the results should be seen as part of a larger, holistic picture of livability and health. Rather than single-handedly resulting from an infrastructural transport connection, the hot spots along the Green Carpet might emerge from a comprehensive, integrative approach tackling multiple environmental and social problems at once. This is indicative of the complexity of the relationship between infrastructure and behavior, and the relationship between livability and health in general. More research is needed to further explore the relationships between sustainable development, livability, and health.

This study has some limitations. First, only 126 of the 31,000 inhabitants of East Maastricht participated in this study. The reconstruction area is known as a deprived area, but more than half of the participants were higher educated, so the results of this study might be subject to selection bias. Further, the follow-up measurement was executed when the Green Carpet area was still under construction. Even though the walking and cycling infrastructure was opened at the time, the real estate and redesigned public open space were not yet completed.

5. Conclusion

This study showed that even though there were no detectable changes in total physical activity on a population level in the short term, this urban reconstruction prioritized for active transport changed the physical activity patterns of residents in the neighborhood. Moreover, the use of the Green Carpet was associated with less transport-based SB and more transport-based and total MVPA in lower educated individuals. Longer-term follow-up measurements are needed to investigate whether the identified differences in physical activity intensity hot and cold spots concern a rerouting of pre-existing travel, or indicate an actual shift in physical activity behavior that will eventually lead to increases in the volume of total daily physical activity in the longer term. Also, more research is needed to further explore the effects of heterogeneity in study samples on the results of experiments.

For urban planners and policymakers, this study shows that following an integrative approach by targeting multiple aspects in the environment, such as improved traffic safety, green space, and connectivity, can lead to changes in the use of public spaces on the short term. In addition, such major infrastructural projects can influence the behavior of different subgroups in society.

In terms of research, this study shows that geospatial analyses help to specify behavioral patterns on locations and routes as input to further explore the relationship between environment and physical activity behavior. It highlights the fact that changes in the built environment can lead to changes in physical activity patterns of individuals, but this does not necessarily lead to changes on population-level physical activity levels. This advocates for more diverse forms of data collection and analysis methods if we are to better understand how the physical environment affects behavior and health.

Declaration of interest

Declarations of interest: none.

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Appendix A. Supplementary data

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