The effects of the built environment on physical activity and health

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A NATURAL EXPERIMENT EVALUATING THE GREEN CARPET IN MAASTRICHT

Nicole Stappers

The research presented in this thesis was conducted at the School of Nutrition and Translational Research in Metabolism (NUTRIM), Department of Health Promotion, Maastricht University. The research was funded by ZonMw and Projectbureau A2 Maastricht.

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The effects of the built environment on physical activity and health

A natural experiment evaluating the Green Carpet in Maastricht

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CHAPTER 1

General introduction

PROBLEM DEFINITION

The population of the southern part of the province of Limburg has been suffering from decreased health status, lower life expectancy and higher prevalence of (non-communicable) chronic diseases compared to the rest of the province and the Netherlands as a whole [1]. There are various explanations for these regional differences, for example the lower socioeconomic status of individuals living in this area, the lower level of education, and the influence of lifestyle factors [1]. In 2020, 54% of the adults in Southern Limburg was overweight, compared to 52.4% of the adults in Northern Limburg and 50% of adults in the Netherlands as a whole [2]. Accordingly, only 44.3% of the adults in Southern Limburg met the physical activity guidelines, in comparison to 52.1% of the adults in Northern Limburg and 52.9% of the adults in the Netherlands as a whole [2].

The lack of physical activity is associated with various non-communicable diseases, such several types of cancer, obesity, type 2 diabetes and cardiovascular diseases [3-6]. Therefore, population-level physical activity levels should increase in order to improve public health and to decrease health care costs [7, 8]. Despite the growing attention for physical activity and its positive effects on health and healthcare costs, worldwide physical activity levels did not significantly change between 2001 and 2016, and about 37% of the population of high-income countries was considered to be physically inactive in 2016 [9]. These numbers are present among the total population, but physical activity during leisure time is more common among higher educated groups, compared to lower educated groups [10, 11]. This difference between more and less vulnerable individuals may be the result of various factors, such as individual lifestyle factors, community networks, and socio-economic, cultural and environmental conditions [12]. One of the causes for the differences in the risk for most major diseases, is the difference in exposure to factors that cause or prevent the disease. Also, the same level of exposure to a risk factor may have different effects on individuals with a different socio-economic position (SEP) [13]. A previous European multi-country study found that residents of low SEP neighborhoods had less favorable perceptions of the environment in their neighborhood, compared to residents of high SEP neighborhoods [14], which might significantly influence physical activity levels. However, experimental evidence regarding the differences in the effects of the environment on physical activity for different SEP groups is lacking [15].

THE SOCIO-ECOLOGICAL PERSPECTIVE

Socio-ecological models can be used to explain how health behaviors are influenced by both personal and environmental factors [16, 17]. Ecological models differ from other behavioral models by also considering environmental and policy level influences, in contrast to models that focus on individual characteristics only. In 1991, Whitehead and Dahlgren published the rainbow model of health determinants [12]. This model explains the interactions between individuals and their environments by placing the individual in the center of the figure, which is surrounded by multiple layers of determinants that interact with the individual [12]. It describes that individual lifestyle behaviors are enclosed in social norms and networks, which are embedded in working and living conditions, which in turn are related to the wider socioeconomic and cultural environment. A change in one of the layers, for example by intervening at one level, can influence the other layers. A change in the environment can thereby result in a change in individual behavior, through the intermediate layers. Specifically for active living research, Sallis et al., proposed a framework for active living policy and environmental research [18]. Comparable to the other models, the individual is placed at the center of the model, which is surrounded my multiple levels of determinants; the perceived environment, behavior, behavior settings and policy environment. The overlapping concepts of these models is that behavior has multiple levels of influences, often including intrapersonal, interpersonal, organizational, community, physical environment and policy [16]. Healthy behaviors are thought to be maximized when environments and policies support healthful choices, and individuals are motivated and educated to make those choices [19]. Therefore, the central idea of ecological models is that it takes the combination of both individual-level and environmental/policy-level interventions to achieve substantial changes in health behaviors [16].

One of the frameworks that describes the effects of the environment on energy balance-related behaviors (EBRBs) such as physical activity is the Environmental Research framework for weight Gain prevention (EnRG) framework [20]. In this dual-process model, it is argued that behavior is the result of direct and indirect effects of the environment. Direct, or unmediated, environmental influences are unconscious, automatic processes. The vast majority of our behavior is influenced by this type of processes. On the other hand, the 'indirect' influences of the environment on physical EBRBs imply that the relationship between environment and behavior is mediated by cognitive factors, such as attitude, perceived behavioral control of environmental factors on physical activity behaviors [20]. The simultaneous influence of both the direct and indirect processes results in a specific behavior. In addition, both the direct and indirect pathway can be moderated by various factors, such as demographic factors, educational level, household income, family climate (parenting, role-models, social norms), personality and awareness. This stresses that the environment can have different effects for different subgroups in society.

Thus, in socio-ecological frameworks, the living environment is recognized as an important determinant for health and well-being. However, in practice, there is a lack of cooperation between health and planning agencies [21]. Even though the principles of modern urban planning originated in response to basic health problems in the 19 century, urban planning and health departments are currently largely separated [22]. In 2006, Barton and Grant proposed a conceptual model which was inspired by the diagram of Whitehead and Dahlgren, but also included concepts of the ecosystem theories (which emphasizes the relationship between people and their environment) and the principle of sustainable development [22]. In contrast to the theoretical frameworks discussed above, this framework focuses on collaboration across professions and topics. Hereby, policymakers are informed how new policies might potentially affect the people at the individual level, as well as the greater natural environment and global ecosystem.

Although socio-ecological models might help to understand and investigate the effect of the environment on health behaviors, it should be noted that these models are a simplified representation of reality. Public health issues such as physical inactivity are complex problems. According to the complex adaptive systems theory, the system in which a specific behavior takes place is constantly adapting to the conditions in time and context [23]. Also, elements of a complex system are interacting within and between different levels. Although the current thesis uses traditional, linear, analyses methodologies, the complexity of reality was not ignored. Therefore, a thorough assessment of the (changing) context in which this evaluation took place was executed, context-specific outcome measures were used and multiple interactions within and between different levels were tested.

EXISTING EVIDENCE/ NEED FOR RESEARCH

Over the past decades, a substantial amount of observational and experimental research has been carried out to explore the impact of the environment on physical activity and health. Several cross-sectional studies evaluated the relationship between subjective and objective attributes of the neighborhood environment on physical activity [24-26]. In 2012, a large European-specific systematic review on the relationship between environmental factors and physical activity concluded that there was convincing evidence on a positive relationship between physical activity and five different environmental factors: walkability, access to shops, services, and work, safety from traffic, degree of urbanization, and quality of the environment [27]. However, the authors noted that there is a discrepancy between factors that play an important role in Europe and countries in other continents. In 2016, a large multi-country cross-sectional study added that combinations of environmental features explained more variation in physical activity than single variables, suggesting that a comprehensive approach is needed to design activity supportive neighborhoods [28].

Despite the large body of evidence regarding cross-sectional relationships between environment and behavior, the amount of experimental evidence is limited. Some built environment interventions can increase active transport, but more research is needed to investigate the effects on total levels of physical activity [29]. Also, the quality of existing experimental studies should improve, especially in terms of the use of context-specific measurements, provision of detailed description of the context in which an intervention takes place, and the inclusion of multiple groups based on the proximity to the intervention [30]. Further, the effects of changes to the built environment on different subgroups in society was rarely studied and needs further research [15, 31]. Lastly, none of the existing studies included sedentary behavior as an outcome measures while it might be an independent risk factor for obesity [32]. Therefore, more and higher-quality experiments are needed to further investigate the effects of the environment on health behavior and health.

THE GREEN CARPET IN MAASTRICHT

The tunneling of a cross-town highway in the city of Maastricht (Southern Limburg, The Netherlands) provided a unique opportunity to design an experiment to investigate the effects of major changes in the built environment on the behavior and health of inhabitants in the adjacent areas. For over 50 years, the highway A2 crossed several (deprived) neighborhoods in the city. At first, the construction of this 'boulevard' in the 1950's was a prestigious project, showing the wealth of the city. However, due to fast industrialization and associated increase in car-use, the highway rapidly became both a physical and social barrier between the neighborhoods at the east and west of it (Figure 1). Also, the highway and associated traffic congestion resulted in poor air quality and poor living conditions for individuals living in the adjacent neighborhoods.

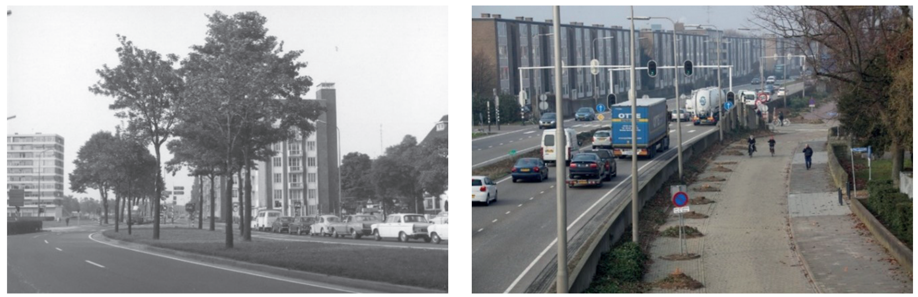

Figure 1. Left: highway A2 as a prestigious boulevard in the 1950's. Right: highway A2 crossing as a physical and social barrier crossing several deprived neighborhoods in the city. Source: Project-bureau A2 Maastricht.

Statistics of the Netherlands Statistics showed that the socioeconomic status of the people living in the areas directly neighboring the highway was lower than average [33]. Before the opening of the tunnel in 2016, about 33-36% of the inhabitants of this area were facing chronic conditions, only 48-49% of the inhabitants met the physical activity guidelines and 44-47% was overweighed [34]. Also, the yearly average concentration of particular matter (PM10) in this area exceeded the standards of the World Health Organization (WHO) [35] and the perceived livability levels of the adjacent neighborhoods were alarming [36].

Already in 1978, it was recognized that the highway should be tunneled or diverted in order to improve the traffic congestion and living conditions . However, the tunnel that relieved the city from traffic was only opened in 2016. The plans for the tunnel and the redesigned area on top of it were politically approved in 2010. The total costs of the project were estimated at €1.2 billon, which was invested by European, national, provincial and local governments, and a contracting party. A 2.3-km long double-layered tunnel was constructed to replace the highway at the same trajectory. The lower tubes of the tunnel facilitate the traffic that pass the city in the direction of Liege and Eindhoven, while the upper tubes of the tunnel facilitate traffic destined for Maastricht and surroundings. On top of the tunnel, two one-way streets accommodate the remaining local traffic. The middle part of the profile is about 6 meters wide, is prioritized for pedestrians, cyclists and recreation, and is separated from the adjacent streets by grass and trees, creating the so-called Green Carpet (figure 2). Also, 1100 new dwellings for private and social housing and 30.000m2 of new commercial spaces are planned alongside the Green Carpet. In 2015, the program ‘My Healthy Green Carpet 2030’ was launched, including eleven actions to reach technical and social sustainability, for example to create an active environment that stimulates physical activity and health [37].

Figure 2. Left: Schematic overview of the tunnel and the Green Carpet on top of it; Middle: Highway A2 crossing the city of Maastricht, during construction of the tunnel; Right: Green Carpet after the opening of the tunnel. Source: Projectbureau A2 Maastricht.

NATURAL EXPERIMENT

The Project Agency A2, which was concerned with the execution of the Green Carpet project, has joined forces with Maastricht University to take advantage of the opportunity to design an experiment to investigate the effects of such major changes on the behavior and health of inhabitants of the adjacent areas. For Maastricht University, this collaboration enabled to design a large-scale experiment that adds new high-quality evidence to the current scientific knowledge-base and get more insights in the relationship between the environment and behavior.

The overall aim of this thesis was to evaluate the effects of major infrastructural redesign project on physical activity levels, active transport, sedentary behavior and perceived health-related quality of life of inhabitants of Maastricht.

It is hardly possible to perform randomized controlled trials to evaluate such large-scale interventions, as it is not possible and unethical to randomly assign people into exposure and control groups. Natural experiments might help to overcome these problems as in this type of studies the exposure to the event or intervention of interest has not been manipulated by the researcher. Natural experiments provide the opportunity to derive more consequential evidence whereby the relationship between changes in exposure and outcome is studied [38]. This type of study works best when the effects of the intervention are large and rapid, and good quality data on exposure and outcomes in a large population are available [39]. These conditions were also the starting point of the experiment described in this thesis.

The design of the effect evaluation in this thesis is a three-armed natural experiment. The three arms of the study are defined based on the distance to the Green Carpet area, and thereby the expected exposure of these inhabitants to the newly designed area. The ‘maximal exposure’ group consisted of individuals that lived in the neighborhoods bordering the Green Carpet, situated at the East side of the city center (Figure 3, dark green). The expected exposure to the Green Carpet, was the largest in this group. The ‘minimal exposure’ group consisted of inhabitants of Maastricht who lived on the western side of the river Meuse and outside the city center. Participants from these suburban areas (figure 3, light green) are living further away from the Green Carpet, which makes it less likely that they were exposed to the Green Carpet. For those two groups, the Green Carpet may provide an add-in opportunity to incorporate physical activity (e.g. in forms of active transport) in the behavioral routines of people living in the adjacent areas.

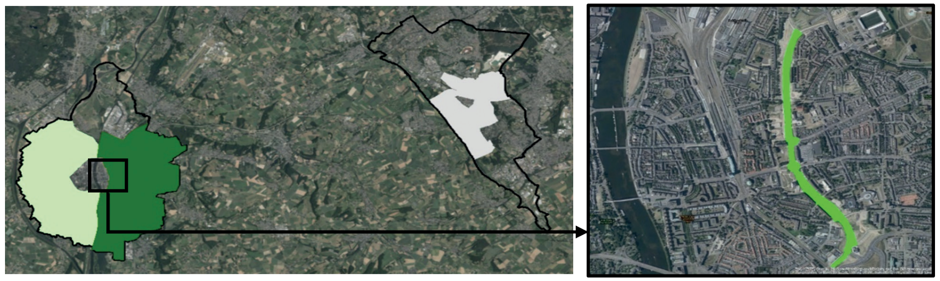

Figure 3. Three area-based exposure groups. Dark green: maximal exposure group in East Maastricht; Light green: minimal exposure group in West Maastricht; White: no exposure group in Heerlen. Cutout, light green: Green Carpet.

Individuals living in the ‘no exposure’ area were inhabitants of the city of Heerlen. Participants of this group were not expected to be exposed to the Green Carpet because they lived approximately 25 kilometers away from the Green Carpet. Heerlen was selected as comparison area because the selected neighborhoods in this city are comparable to Maastricht with regard to the number of inhabitants, urbanization and the geographical and cultural context.

The baseline measurement took place in 2016/2017, before the Green Carpet was opened. The tunnel opened in several phases between December 2016 and spring 2017. Thereafter, the construction of the Green Carpet started. In April 2018, the Green Carpet was officially put into use. From august 2018 until July 2019, the first follow-up measurement took place. A last round of measurements was executed from September 2020 until July 2021.

Outcome measures of the current evaluation are context-specific physical activity levels, active transport, sedentary behavior, and self-reported health-related quality of life.

Novel techniques for measuring context-specific physical activity levels

Physical activity measurements can be roughly divided into time-specific and context-specific measurements. Time-specific measurements determine the total amount of physical activity in a certain length of time, regardless of the environment in which it took place. Over the past decades, several device-based (e.g., accelerometers and pedometers) and subjective (e.g., the International Physical Activity Questionnaire [IPAQ]) time-specific physical activity measurements have been developed [40].

Context-specific physical activity measurements assess the amount of physical activity in a specific physical environment. This might be of special interest when examining the effects of a certain environment on behavior in that environment. An example of a subjective

measure for context-specific physical activity is the neighborhood-adapted version of the IPAQ (N-IPAQ), which assesses physical activity levels in the home neighborhood [41]. On the other hand, a combination of accelerometers and global positioning systems (GPS) can be used to perform device-based measurements to determine context-specific physical activity levels [42]. It is widely recognized that objective and subjective measurements of physical activity may lead to inconsistent outcomes [43]. Research also suggests that using time-specific or context-specific measurements of physical activity leads to differences in their association with the built environment [44]. To date, almost all existing research used time-specific physical activity measurements. However, when examining changes in a specific context without taking this context into account in the measurements, this might lead to inconsistent and inconclusive results. The current thesis will add to the existing knowledge by using context-specific measurement in order to further understand the relationship between environment and behavior. Thereby, it is possible to investigate the relationship between specific environments and different types of physical activity (e.g. active transport) in more detail.

THIS DISSERTATION

The overall aim of this dissertation was to evaluate the effects of the Green Carpet on physical activity, sedentary behavior, and health-related quality of life. This aim is subdivided into four subgoals.

I. To systematically review the existing evidence regarding the effects of major infrastructural interventions on physical activity, sedentary behavior and active transport.
II. Explore cross-sectional relationships between the perceived neighborhood walkability and (context-specific) physical activity and sedentary behavior.
III. Evaluate short- and longer term effects of the realization of the Green Carpet on physical activity, sedentary behavior, active transport and health-related quality of life.
IV. Investigate the effect of (changing) context on design, implementation and evaluation of major urban reconstructions.

Lastly, we aimed to explore differences in the relationship between the environment and behavior for more or less advantaged individuals in society.

In **chapter 2**, a systematic review is presented in which existing experimental studies are included that evaluate the effects of built environmental infrastructural changes on physical activity and sedentary behavior. In **Chapter 3,** we zoom out to understand the complex interplay between the infrastructural project and the various actors, interests and dynamics during the 15 year planning and construction processes. The chapter describes how various types of context impacted on the origin, design and execution of the Green Carpet project. This is done in a qualitative study based on interviews with stakeholders, desk research and observations. From **chapter 4** on, we zoom in to the specific relationships between (perceptions of) the environment, behavior and health-related quality of life. **Chapter 4 and 5** discuss cross-sectional relationships between perceptions of the built environment on total physical activity levels (chapter 4) and physical activity in the home neighborhood (chapter 5). Both chapters are based on the baseline measurement of the effect evaluation. **Chapter 6 and 7** include analyses based on the baseline and first follow-up measurement. **Chapter 6** focusses on the short-term effects of the Green Carpet on total and transport-based physical activity levels. In **chapter 7**, geospatial analyses were performed to evaluate how physical activity behavioral patterns actually changed after the construction of the Green Carpet. **Chapter 8** discusses the longer-term effects of the Green Carpet on total and transport-based physical activity levels, and its impact on health-related quality of life. **Chapter 9** presents a general discussion on the studies presented in this dissertation.

CHAPTER 2

The effect of infrastructural changes in the built environment on physical activity, active transportation and sedentary behavior – A systematic review

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ABSTRACT

This systematic review examined the effect of built environment infrastructural changes (BEICs) on physical activity (PA), active transportation (AT) and sedentary behavior (SB). A literature search resulted in nineteen eligible articles. On- and off-road bicycling and/or walking trails resulted in inconsistent effects on overall PA and walking, and in predominantly positive effects on bicycling. More extensive BEICs led to mixed results, with mainly non-significant effects. However, positive effects on bicycling were found for people living closer to BEICs. None of the studies assessed SB. Improved understanding of the potential of BEICs to increase PA levels and decrease SB at population level asks for more high-quality, in-depth research, that takes into account the broader system.

INTRODUCTION

In recent decades, the prevalence of obesity has increased in most countries and regions of the world [45]. Public health experts agree that the rapid rise in obesity cannot be explained by changes in genes, biology and psychology at the individual level alone. The explanation should also be sought in broader environmental, policy and societal changes [46, 47]. As the choices people make are partially shaped by the environments in which they live, efforts to reduce obesity, type II diabetes and cardiovascular diseases by interventions at individual level need to be supported and augmented by a whole-system response that includes upstream health policies, infrastructural changes and legislation [48, 49]. Hence, researchers and policy makers are increasingly interested in environmental and policy interventions as strategies for population-wide improvements in physical activity (PA) and eating habits, in order to reduce and prevent obesity and associated non-communicable diseases [47, 50].

In recent years, a broad range of environmental interventions have been implemented to improve PA levels, for example by installing outdoor exercise equipment, reconstructing playgrounds and increasing the amount of open green space [51, 52]. In addition, a growing number of built environment infrastructural changes (BEICs) aim to promote active transportation (AT) – walking and bicycling for transportation. An example of a BEIC is the implementation of a walking and bicycling trail, aiming to replace passive, sedentary, transportations by AT [53]. BEICs have the potential to promote and sustain behavioral changes over a longer period of time [47, 54]. The built environment (BE) not only promotes or inhibits PA and AT, but can also play a role in reducing sedentary behavior (SB). The SOS (Systems of Sedentary behavior) framework emphasizes the role of the built and natural environments in interrupting sedentary time [55], which is crucial in order to reverse the global trend toward increased sedentary time [56] and physical inactivity [57]. Previous studies found that presence and proximity of green spaces is negatively correlated with SB [58]. Also, BEICs aiming to promote AT might evoke a modal shift from sedentary motorized transportation to AT, leading to both a decrease in SB and an increase in PA.

Cross-sectional studies have found positive associations between the BE and PA, mental health, physical health and well-being [28, 59, 60], but longitudinal and experimental studies are necessary to detect causal relationships between the BE and health outcomes. In general, it is hardly possible to perform randomized controlled trials to evaluate large-scale policy and environmental interventions, as researchers usually cannot influence such interventions and participants cannot be randomly assigned to intervention or control sites. Natural experimental studies might help to overcome these problems. In this type of studies, the exposure to the event or intervention of interest has not been manipulated by the researcher [39]. In the literature, the terms “natural experiments” and “quasi-experiments” are inconsistently used. In both types of experiments, researchers cannot randomly assign participants to an intervention or control condition. Typically, in quasi-experiments researchers have a certain degree of control over the intervention, while the intervention or event of a natural experiment occurs outside the reach of researchers [61].

Previous systematic reviews evaluated the effects of several types of changes in the BE on PA levels and found that infrastructural interventions targeting AT in particular can lead to increased PA [15, 29]. One recent systematic review concluded that the evidence on the effect of the BE on PA is not strong enough to draw conclusions [62]. However, these reviews included a broad range of BE interventions, such as park improvements, infrastructural changes and changes to the public transport infrastructure. The heterogeneity of these interventions makes it difficult to evaluate the actual effect on PA and/or AT. Focusing on BEICs aiming to promote PA and/or AT may lead to more clarity regarding the effectiveness of this specific type of interventions. In addition, previous systematic reviews included participants in all age ranges, while barriers and facilitators to engage in PA and/or AT are different for different age groups. Also, none of the previous reviews searched for studies reporting SB.

The current review builds on the main outcomes of Mayne’s and Smith’s review by assessing the specific effectiveness of different types of BEICs that aim the promotion of PA and/or AT to clarify the effectiveness of this type of interventions in adults. Therefore, the aim of this systematic review is to update and specify the evidence in this field of research by reviewing experimental studies that have examined the effects of different types of infrastructural interventions on PA, AT and SB in adults.

METHODS

Search and selection procedure

A literature search was conducted using PubMed and Web of Science to identify articles examining the effects of BEICs on PA, AT and/or SB, published up to February 2018. The following keywords/terms were included in the search: adult AND built environment OR changes in built environment OR infrastructure OR changes in infrastructure OR path OR trail OR bicycle path OR footpath AND motor activity [MeSH] OR physical activity OR active travel* OR active transport*, OR walking OR bicycling OR exercise OR sport OR sedentary OR sedentary behavior OR natural experiment* OR quasi experiment*. Searches were not restricted by date of publication.

Studies were eligible if: (1) they were a quasi- or natural experiment and had a pre-post design, (2) the BEIC directly targeted the increase of AT and/or transport-related PA (3) PA and/or AT and/or SB was reported, (4) these were assessed in adults, and (5) the articles were written in English. Studies were excluded if they (1) examined BEICs that were not directly aimed to increase transport-related PA and/or AT, such as the implementation of playgrounds, parks or public transit, the placement of fitness equipment, or other non-infrastructural interventions, (2) evaluated health promotion programs or behavior change programs, (3) concerned qualitative research, systematic reviews, conference proceedings or grey literature (4) included children or adolescents younger than 18 years. After duplicates had been removed, titles of all records were screened independently by two reviewers (NEHS, DHHVK). Articles selected by one or both researchers were subjected to abstract screening. Again, both reviewers (NEHS, DHHVK) performed this screening independently, and ineligible studies were removed from the sample. Disagreements between reviewers about eligibility for full-text assessment were resolved by discussion, which was necessary in five cases. The full texts of the remaining articles were assessed by one researcher (NEHS). Reference lists from selected studies were hand-searched for additional articles not retrieved by the electronic search.

One reviewer (NEHS) extracted the following information from each included study: author(s), publication year, study location, description of intervention, study population, study design, control sites, PA outcome measures, AT outcome measures, measuring methods, timing of the measurements and main findings.

Risk of bias assessment

The quality of the included studies was assessed using the adapted version of A Cochrane Risk of Bias Assessment Tool: for Non-Randomized Studies of Interventions (ACROBAT-NRSI), by following the detailed scoring protocol. The adapted version of the ACROBAT-NRSI, including signaling questions, was constructed and published by Benton et al. [63]. Aspects which were adapted are specific for the field of natural experiments and quasi-experiments, such as control site selection and measuring exposure to intervention. In addition, the assessment of internal validity was supplemented with the assessment of two other types of validity (statistical conclusion validity and construct validity). The following domains of bias were included in the risk of bias assessment: Bias due to confounding, bias in selection of participants into the study, bias in measurement of interventions, bias due to departures from intended interventions, bias due to missing data, bias in measurement outcome and bias in the selection of reported results (Table 1). We were aware that the ACROBAT-NRSI might set the bar of methodological acceptability too high, leading to downgrading of evidence from natural experiments [64], but nevertheless considered this tool suitable for comparing the included studies with each other, rather than judging them by the absolute score. A random 33% sample of the included studies were assessed for the risk of bias assessment by two researchers. The results of the assessments were compared and discussed until consensus was reached. The remaining included studies were assessed accordingly by one researcher (NEHS).

RESULTS

Study selection

Figure 1 shows the numbers of publications identified, screened, assessed for eligibility and included. In total, 4163 articles were identified through database searching and checking reference lists. After removing duplicates, 3265 publications remained in the sample, 3170 of which were excluded after title screening. Ninety-five abstracts were reviewed, 47 of which were excluded (list provided in Supplementary file 1). The full texts of the remaining 48 articles were assessed, and 19 articles were included in this systematic review.

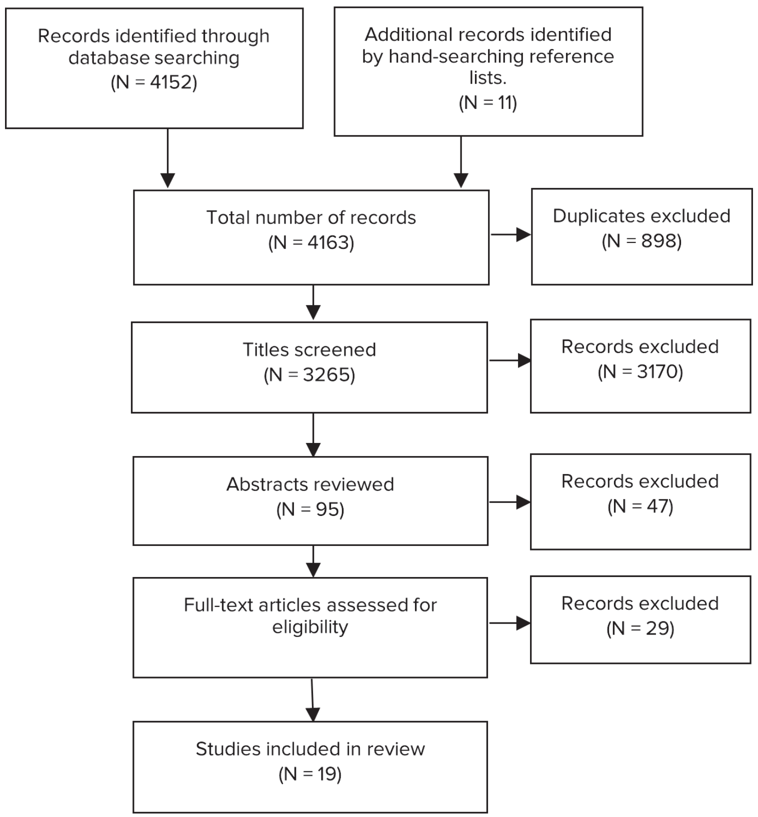

Figure 1. Flowchart of article selection.

Risk of bias

The risk of bias in the included articles varied from moderate [65-67] to serious [68-74] and critical [53, 75-82] (Table 1). None of the included articles scored low for risk of bias. Risk of bias was lowest in the domains of "bias due to departures from intended interventions" and "bias due to missing data". Risk of bias was highest in the domains of "bias in the selection of participants into the study", "bias in measurement outcome" and "bias in the selection of reported results". A fully justified sample size calculation was missing for most of the included studies, except for Pazin et al. (2016) [80]. Outcome measurements were assessed subjectively in the vast majority of the studies. Only Goodman et al. (2014) and Crane et al. (2017) reported the results of more than one follow-up [65, 68]. Study protocols were published for three out of fourteen unique interventions [83-85], making it difficult to judge whether analyses and outcome measures used were pre-specified or were selected on the basis of the results from multiple outcome measures, multiple analyses or the use of multiple subgroups.

Study characteristics

The study characteristics of the 19 included studies are presented in Table 2. In total, fourteen unique BEICs were evaluated. The studies were divided into two categories, based on the magnitude of the BEICs. A distinction was made between single on- and off-road bicycling and/or walking trails and trails that were part of more extensive BEICs that affected the total infrastructural system. Eleven studies were assigned to the category on- and off-road walking and/or bicycling trails [53, 68, 69, 72, 73, 75, 76, 79-82]. Eight studies were assigned to the category of BEICs affecting total infrastructural system [65, 66, 70, 71, 74, 77, 78, 86]. Three BEICs were evaluated in multiple articles; the Connect2 project, UK [65, 67, 74], the construction of a 25 km off-road guideway for buses with parallel walking and/or bicycling path in Cambridgeshire, UK [66, 70, 71] and the implementation of 2.4 km cycling path in Sydney, Australia [68, 73]. Moreover, in three cases BEICs in the same city and context were evaluated in two separate studies [72, 77-79, 81, 82]. These studies were marked as unique interventions since they evaluated unique BEICs during another time path.

Sample sizes of included studies ranged from 169 to 1906 participants (West et al., 2011 [81]; Song et al., 2017 [74], respectively) of which two studies included both children and adults in their systematic observations [72, 79]. We chose to keep these articles in our review, as the studies reported that very few children were observed. Five studies did not provide the exact number of participants, as a result of the study design [72, 76-79]. The BEICs were completed between 2000–2007 and 2014, baseline measurements were performed between 2000 and 2013 and follow-up measurements took place between 2002 and 2014. Follow-up measurements were executed between two and thirty months after opening of the intervention. The time between the openings of the intervention varied between and within studies. Six articles evaluating four unique interventions had a twelve-month period or longer between initial opening of the intervention site and follow-up measurement for all participants [66, 68, 70, 71, 76, 80]. In two studies, the time between the opening of the intervention and follow-up measurement was more than twelve months for at least a part of the sample (7–21 months and 9–14 months, Goodman et al., 2014 [65]; Panter et al., 2016 [71], respectively). For the studies of Hirsch et al. (2017) and Krizek et al. (2009), exact opening dates of the BEICs were not stated, but given the amount of time between baseline and follow-up ~10 years – we assumed that the follow-up measurement was performed more than twelve months after the implementation of the BEICs [77, 78].

Outcome measures included time spent walking, bicycling, moderate physical activity (MPA), vigorous physical activity (VPA), moderate-to-vigorous physical activity (MVPA), total PA, recreational PA, recreational MVPA, recreational PA near home, number of bicyclists and walkers, time spent walking on the commute, time spent cycling on the commute, changes in commute mode share, journey stages in AT, and numbers of bicycle and walking trips.

Outcome measures were divided into five categories; overall PA (MPA, VPA, MVPA, total PA, recreational PA, recreational MVPA, recreational PA near home), walking (time spent walking in leisure time or commuting, walking trips, number of walkers), bicycling (time spent cycling in leisure time or commuting, bicycling trips, number of cyclists), walking and bicycling (active commute mode share, active transport/ active commuting, walking and bicycling on the commute) and SB (time spent sitting). Seven studies used objective measures to assess PA and AT, three of which used direct observation [72, 76, 79]. Two studies evaluating one intervention used electronic counters to count bikes [68, 73]. One used accelerometry and a Global Positioning System (GPS) [75] and one used a mobile phone application [69]. Subjective measurements included telephone surveys, questionnaires, 7-day commute travel diaries and 7-day recall instrument.

Table 1. Results risk of bias assessment

	Bias due to confounding	Bias in selection of participants into the study	Bias in measurement of interventions	Bias due to departures from intended interventions	Bias due to missing data	Bias in measurement outcome	Bias in the selection of reported results	Total
Dill et al. 2014 [75]	Moderate	Moderate	Serious	Critical	Serious	Moderate	Moderate	**Critical**
Evenson et al. 2005 [53]	Critical	Moderate	Moderate	Serious	Moderate	Serious	Critical	**Critical**
Fitzhugh et al. 2010 [76]	Serious	Critical	Moderate	Low	Low	Moderate	Moderate	**Critical**
Heesch et al. 2016 [69]	Moderate	Serious	Serious	Low	Moderate	Serious	Serious	**Serious**
Rissel et al. 2015 [73]	Moderate	Serious	Moderate	Low	Low	Serious	Serious	**Serious**
Crane et al. 2017 [68]	Moderate	Serious	Moderate	Low	Moderate	Serious	Serious	**Serious**
Parker et al. 2011 [79]	Serious	Critical	Serious	Low	Low	Serious	Moderate	**Critical**
Parker et al. 2013 [72]	Serious	Serious	Moderate	Low	Low	Serious	Serious	**Serious**
Pazin et al. 2016 [80]	Moderate	Moderate	Moderate	Moderate	Low	Critical	Critical	**Critical**
West et al. 2011 [81]	Critical	Serious	Moderate	Serious	Moderate	Serious	Critical	**Critical**
West et al. 2015 [82]	Moderate	Serious	Moderate	Moderate	Low	Critical	Critical	**Critical**
Goodman et al. 2014 [65]	Moderate	Moderate	Low	Low	Low	Moderate	Moderate	**Moderate**
Song et al. 2017 [74]	Moderate	Moderate	Low	Low	Low	Moderate	Serious	**Serious**
Panter et al. 2017 [67]	Moderate	Moderate	Low	Low	Low	Moderate	Moderate	**Moderate**
Heinen et al. 2015 [70]	Moderate	Moderate	Moderate	Low	Low	Moderate	Critical	**Serious**
Heinen et al. 2017 [66]	Moderate	Moderate	Moderate	Low	Low	Moderate	Moderate	**Moderate**
Panter et al. 2016 [71]	Moderate	Serious	Serious	Serious	Low	Moderate	Moderate	**Serious**
Hirsch et al. 2017 [77]	Serious	Critical	Moderate	Moderate	N.I.	Serious	Serious	**Critical**
Krizek et al. 2009 [78]	Critical	Serious	Serious	Moderate	N.I.	Serious	Moderate	**Critical**

Results per type of intervention

Table 3 describes the effects of BEICs on PA, walking, cycling and SB and the effect of proximity to the intervention on outcome measures, per intervention type. Key findings are presented in Table 4.

On- and off-road bicycle and/or walking trails

Eleven studies evaluated the effects of on- and off-road bicycle and/or walking trails on overall PA, walking and bicycling. The effects of on- and off-road bicycle and/or walking trails on overall PA were mixed. Two studies reported increases in PA [76, 81] and two reported no significant changes [75, 82]. One study reported decreases in VPA, but no changes in MVPA [53]. Regarding walking, the results were mixed as well. Two studies reported increases in walking [76, 81], and three reported no significant changes [53, 75, 82]. Eight studies reported bicycling of which the majority reported increases in at least one outcome measure [69, 72, 73, 76, 79, 87]. One study reported decreases in bicycling [75]. None of the studies assessed SB. Four studies investigated the effect of proximity to the intervention area on the outcomes [68, 80-82]. One study found that living closer to the intervention led to more overall PA and walking [80], and one study found that living between 1.0 and 2.99 km from the intervention area was associated with a higher increase of cycling compared with individuals living closer (< 1.0 km) or further away (> 3.0 km) [68]. Two other articles did not report any significant interaction [81, 82].

Table 2. Study characteristics of included studies.

Author, year	Study location	Description BEICs	Study population	Study design	Control sites/ exposure groups	Outcome measures	Measurement method	Timing follow-up
On- and –off-road walking and/or bicycling trails								
Dill et al., 2014 [75]	Portland, Oregon, USA	Installation of eight 0.9 – 4.2 mile long bicycle boulevards (streets with low motorized traffic volumes and speeds, designated and designed to give bicycle travel priority)	293 adults with children from Family Activity Study. Divided into treatment (N=154) and control (N=139) groups. Able to ride a bicycle, access to a working bicycle	Natural experiment; longitudinal panel design with control group	11 control street segments (1.0 to 5.7 miles long), similar in urban form and demographic characteristics, often parallel streets several blocks away	MVPA (min/week); Made a walking trip (Y/N); Number of walking trips; Walking > 20 min (Y/N); Walking (min/week, if >20); Made a cycling trip (Y/N); Number of cycling trips; Cycling > 10 min (Y/N); Cycling (min/week, if>10)	Objective; accelerometry and GPS	Baseline: Jul. 2010 – Nov. 2010 April 2011 – Sept. 2011 Trail opened: N.I. Follow-up: Aug. 2012 – Nov. 2012 Apr. 2013 – Aug. 2013 Exposure: 2 – 12 months (reported)
Evenson et al., 2005 [53]	Durham, North Carolina, USA	Extension of a 3.2-mile rail-to-trail conversion (10 ft wide and paved for pedestrians, bicyclists and others) by 2.8 miles, along with a 2.0-mile spur	366 adults (≥18 y) living within 2 miles of the trail.	Quasi-experimental pre-post design without control group.	N.A.	Leisure activity (min/week); Leisure activity near home (min/week); Total walking (min/week); Total cycling (min/week); MPA (min/week); VPA (min/week); Walking for transportation (min/week); Cycling for transportation (min/week)	Subjective; Telephone survey following the BRFSS	Baseline: Jul. 2000 – April 2001 Trail opened: Sep. 2002 Follow-up: Nov. 2002 Exposure: 2 months (calculated)
Fitzhugh et al., 2010 [76]	Knoxville, Tennessee, USA	Construction of an 8-foot-wide and 2.9-mile-long asphalt greenway providing pedestrian-friendly links among residences, businesses, schools and other public spaces.	Children, adolescents and adults in free-living conditions.	Quasi-experimental research design with multiple control neighborhoods.	One intervention neighborhood. Two control neighborhoods matched on socioeconomic dimensions.	2-hour count of overall PA; 2-hour count of walkers; 2-hour count of cyclists	Objective; Direct observation	Baseline: Mar. 2005 Trail opened: Dec. 2005 Follow-up: March 2007 Exposure: 14 months (reported)

Table 2. Study characteristics of included studies. (continued)

Author, year	Study location	Description BEICs	Study population	Study design	Control sites/ exposure groups	Outcome measures	Measurement method	Timing follow-up
Heesch et al. 2016 [69]	Brisbane, Queensland, Australia	Construction of a 2.3 km long segment, as a part of an 17 km long, 3 meter wide off-road bikeway.	Adults in free-living conditions.	Natural experiment.	One intervention trail, one existing off-road biking trail and one major arterial road without lane markings for bicycles.	Bicycle counts per month	Objective; Strava mobile phone application	Baseline: August 20th , 2009 Trail opened: June 25 2013 Follow-up September 18th, 2013 Exposure: 3 months (calculated)
Parker et al., 2011 [79]	New Orleans, LA, USA	A 3.1 mile bike lane was located between the outside travel lanes and the parking lane alongside Louisiana Highway 46. Bike lanes were striped on both sides of the road and lanes are 5 ft (1.52 m) wide.	Men, women, adults and children riding a bicycle with traffic, against traffic and on Sidewalks.	Quasi-experiment without control group.	N.A.	Number of cyclists	Objective; Direct observation	Baseline: Nov. 2007 Trail opened: Spring 2008 Follow-up: Nov. 2008 Exposure: 6 months (reported)
Parker et al., 2013 [72]	New Orleans, LA, USA	A 1-mile bikelane which was striped on both sides of the road and 5ft (1.52 m) wide. Bikelanes were located between the travel lane and the parking lane.	Men, women, adults and children riding a bicycle with traffic, against traffic and on sidewalks.	Quasi-experiment.	One intervention street. Two control streets without bike lane one block off the intervention street.	Number of cyclists	Objective; Direct observation	Baseline: September 2009 Trail opened: June 2010 Follow-up: September 2010 Exposure: 3 months (calculated)
Pazin et al., 2016 [80]	Florianop-olis, SC, Brazil	New avenue, parking lots, and an on-road walking and cycling route (2.3 km long) along the seashore. A new project is in preparation to add 8.3 km to this walking and cycling route.	745 adults (>18y) living in six neighborhoods within 1500 m from the new route.	Longitudinal quasi-experiment.	Participants were assigned to one out of three groups based on exposure to the intervention: 0-500 m, 501 – 1000 m and 1001 – 1500 m.	Leisure-time PA (min/week); Walking (min/week); MVPA (min/week); Walking + MVPA (min/ week)	Subjective: IPAQ	Baseline: Mar. 2009 – Jul. 2009 Trail opened: July 2010 Follow-up: Mar. 2012 – Dec. 2012 Exposure: 20-29 months (reported)

Table 2. Study characteristics of included studies. (continued)

Author, year	Study location	Description BEICs	Study population	Study design	Control sites/ exposure groups	Outcome measures	Measurement method	Timing follow-up
1) Rissel et al., 2015 [73] 2) Crane et al., 2017 [68]	Sydney, New-South Wales, Australia	A new 2.4 km bi-directional separated bicycle path in inner Sydney.	512 (1) and 418 (2) adults (18-55y) who had ridden a bicycle before and had no current disability preventing them from riding, divided into an intervention (n=240 (1), n=189 (2)) and control group (n=272 (1), n=229 (2)). Intervention group lived not more than 2.5 km away from the bicycle path.	Longitudinal, quasi-experiment.	1) Participants in the intervention area lived within 2.5 km from the intervention area. Participants in the comparison area lived in neighborhoods with a similar distance from the central business district and with a similar demographic profile. 2) Participants were assigned to one of three groups based on proximity to the intervention: living within 1.0 km, between 1.0-2.99 km and living >3 km away from intervention area.	Number of cyclists; Weekly frequency of cycling (min/week); Cycling duration (min/week); Travel to work by bicycle	Objective: Fixed electronic bike counts Subjective: 7-day travel diary	Baseline: Sep. 2013 – Okt. 2013 Trail opened: N.I. 1) Follow-up I: Sep. 2014 – Okt. 2014 Follow-up II: 1 + 2) Sep. 2015 - Nov. 2015 Exposure: 1) 4 months (reported) 1+ 2) 16 months (calculated)
West and Shores, 2011 [81]	Midsized Southeast-ern US city	5 miles of greenway were developed and added to an existing greenway along a river in a midsized Southeastern US city.	169 property owners living within .50 miles (n=95) and within .51 and 1.0 miles (n=74) of the greenway.	Quasi-experimental design with control group	Participants were assigned to one of two groups based on exposure to the intervention: living within .50 miles and living .51-1.0 miles away from intervention.	Walking (days/week); MPA (days/week); VPA (days/week)	Subjective: Questionnaire	Baseline: Dec. 2007 Trail opened: early 2008 Follow-up: Dec. 2008 Exposure: 11 months (reported)

Table 2. Study characteristics of included studies. (continued)

Author, year	Study location	Description BEICs	Study population	Study design	Control sites/ exposure groups	Outcome measures	Measurement method	Timing follow-up
West and Shores, 2015 [82]	Charlotte, North Carolina, USA	1.93 miles of greenway was developed and added to an existing greenway.	203 Property owners living within 1 mile of the greenway (n=118) or 2-3 miles from the greenway. (n=85)	Quasi-experimental design with control group.	Participants in intervention group lived within 1 mile from the intervention. Participants of the control group lived within 2.0-3.0 miles from the intervention.	Walking (days/week); MPA (days/week); VPA (days/week)	Subjective: Questionnaire	Baseline: Dec. 2009 Opening: 2010 Follow-up: 2011 Exposure: Little less than 1 year (reported)
BE infrastructural change affecting total infrastructural system.								
1) Goodman et al., 2014 [65]; 2) Song et al., 2017 [74]; 3) Panter et al., 2017 [67]	Cardiff, Kenilworth and Southampton, UK	Construction of a traffic-free bridge in Cardiff and Kenilworth and the conversion of an informal riverside footpath into a boardwalk in Southampton. Improvement and development of existing and feeder routes.	Randomly selected adults (≥18 y) living within 5km from core projects. 1796 (1) and 1906 (2) residents participated at follow-up I and 1465 (1), 1564 (2) at follow-up II. 1257 (3) participated in both follow-ups.	Quasi-experimental cohort study.	An individual measure of proximity was used to represent exposure to intervention.	Walking and cycling for transportation and recreation (min/week); Overall PA (min/week); MVPA other than walking and cycling (min/week); Walking for transportation (min/week); Cycling for transportation (min/week)	Subjective; IPAQ 7-day recall instrument	Baseline: Apr. 2010 Trail opened: Southampton and Cardiff – Jul. 2010 Kenilworth – Sep. 2011 Follow-ups (1 & 2-year): Ap. 2011 Apr. 2012 Exposure: Southampton and Cardiff: 9 and 21 months Kenilworth: 0 and 7 months

Table 2. Study characteristics of included studies. (continued)

Author, year	Study location	Description BEICs	Study population	Study design	Control sites/ exposure groups	Outcome measures	Measurement method	Timing follow-up
1) Heinen et al., 2015 [70]; 2) Heinen et al., 2017 [66]; 3) Panter et al., 2016 [71];	Cambridgeshire, UK	Construction of a 25 km off-road guideway for buses, with a parallel path for walking and cycling.	Cohort of 470 (1), 347 (2) and 469 (3) adults (≥16 years) working in areas of Cambridge to be served by the busway and living within approximately 30 km of the city center;	Quasi-experimental cohort study.	An individual measure of proximity was used to represent exposure to intervention.	Change in commute mode share; Mode(s) of travel to and from work; Walking and cycling for recreation (min/week); Walking for recreation (min/week); Cycling for recreation (min/week); Total walking and cycling (min/week); Total walking (min/week); Total cycling (min/week); Total recreational physical activity (min/week); Total physical activity (min/week) Active commuting (min/week); Walking on the commute (min/week); Cycling on the commute (min/week)	Subjective; RPAQ 7-day commute travel diary	Baseline: May 2009 – Okt. 2009 BEIC opened: Aug. 2011 Follow-up: May 2012 – Okt. 2012 Exposure: 9 – 14 months (reported)
Krizek et al., 2009 [78]	Minneapolis, Minnesota, USA	Installation of on- and off-street bicycle lanes (total of 14 km and 25 km, respectively), short lane striping.	Adults living in Minneapolis/St. Paul. Exact number not provided.	Repeat cross-sectional with comparison group	An area-based measure of proximity was used to represent exposure to intervention.	Proportion of bicycle commuters among all commuters;	Subjective; US Census – The Census Transportation Planning Package	Baseline: 1990 Trails opened: During study period (1990-2000) Follow-up: 2000 Exposure: N.I.

Table 2. Study characteristics of included studies. (continued)

Author, year	Study location	Description BEICs	Study population	Study design	Control sites/ exposure groups	Outcome measures	Measurement method	Timing follow-up
Hirsch et al., 2017 [77]	Minne-apolis, Minnesota, USA	Addition of two off-road paved paths (total length of 10.2 miles), transecting the city north-south and east-west, including a dedicated bicycle/pedestrian bridge over a busy freeway.	Employees of 16 years and older, living in one of the 116 selected tracts in the Minneapolis/ St. Paul area.	Longitudinal repeated cross-sectional study.	An area-based measure of proximity was used to represent exposure to intervention.	Change in proportion of bicycle commuting	Subjective; Census 2000 and American Community Survey 2008-2012	Baseline: 2000 Trails opened: Components were constructed between 2000 and 2007 Follow-up: 2008-2012 (5-year average) Exposure: N.I.

BRFSS = Behavioral Risk Factor Surveillance System; IPAQ= International Physical Activity Questionnaire; RPAQ= Recent Physical Activity Questionnaire

Built environment infrastructural changes affecting the total infrastructural system

Eight studies evaluated four unique BEICs affecting the total infrastructural system. The implementation of traffic free bridges and an informal boardwalk, and a busway with parallel walking and/or cycling trail resulted mainly in non-significant and negative effects on overall PA, walking, bicycling, walking and bicycling [65-67, 70, 71, 74]. Two studies found positive effects. Hirsch et al. (2017) and Krizek et al. (2009) both found increases in bicycling after the interventions [77, 78].

For all four BEICs affecting the total infrastructural system, the included studies tested whether proximity to the intervention area was associated with changes in PA outcomes. All studies found non-significant or positive associations between proximity to the intervention area and PA outcomes. Proximity to the intervention was associated with more overall PA and more walking and bicycling at the second follow-up of Goodman et al. (2014), 9–21 months after the implementation of the BEICs, but not at the first follow-up after 0–9 months [65]. Also, living closer to the busway and the BEICs in Minnesota resulted in more bicycling and combined walking and bicycling compared to living further away [66, 77, 78].

Table 3. Study characteristics of included studies.

Author(s) (year)	Intervention type		Results					Results based on proximity to intervention[a]				
	On- and off-road bicycling/ walking trail	BEICs affecting the total infrastructural system	Overall PA	Walking	Bicycling	Walking and bicycling/ active commuting	SB	Overall PA	Walking	Bicycling	Walking and bicycling/ active commuting	SB
Dill et al. 2014 [75]	•		0	0	0/-							
Evenson et al. 2005 [53]	•		0/-	0	0							
Fitzhugh et al. 2010 [76]	•		+	+	+							
Heesch et al. 2016 [69]	•				+							
Rissel et al. 2015 [73]; Crane et al., 2017 [68]	•				+/0			0		+		
Parker et al. 2011 [79]	•				+							
Parker et al. 2013 [72]	•				+							
Pazin et al. 2016 [80]	•							0/+	+			
West et al. 2011 [81]	•		+	+				0	0			
West et al. 2015 [82]	•		0	0				0				
Goodman et al. 2014 [65]; Song et al. 2017 [74]; Panter et al. 2017 [67]		•	0/-	-	0	0		0/+	0/+		0/+	
Heinen et al. 2015 [70]; Heinen et al. 2017 [66]; Panter et al. 2016 [71]		•	0	0	-	0/-		0	0	+	0/+	
Hirsch et al. 2017 [77]		•			+					+		
Krizek et al. 2009 [78]		•			+					+		

Table 4. Key findings of included articles

Author , year	On- and –off-road bicycling/ walking trails	BEICs affecting total infrastructural system	Overall PA	Walking	Bicycling	Walking and bicycling / Active commuting	SB
Dill et al., 2014 [75]	•		No changes	No changes	Living in the intervention area was negatively correlated with minutes of cycling and number of cycling trips.	N.A.	N.A.
Evenson et al., 2005 [53]	•		VPA decreased at follow-up for both users and non-users of the trail. MPA decreased for non-users	No changes in overall sample. Participants who used the trail were less likely to increase their walking by >30 min or 45 min per week	No changes in overall sample. Minutes per month bicycling for transportation decreased for those who never used the trail. Participants who used the trail were more likely to decrease bicycling time	N.A.	N.A.
Fitzhugh et al., 2010 [76]	•		After intervention, total count of PA was significantly higher in experimental neighbourhoods compared to control neighbourhoods. In experimental neighbourhoods, total PA increased over time. In control neighbourhoods, total PA decreased over time.	Number of walkers was significantly higher in experimental neighbourhood at follow-up. Changes in walking significantly differed between experimental and control group.	Number of cyclists was significantly higher in experimental neighbourhood at follow-up. Changes in cycling significantly differed between experimental and control groups	N.A.	N.A
Heesch et al., 2010 [69]	•		N.A.	N.A.	The GPS bicycle counts increased monthly at the intervention trail and did not change on the other routes.	N.A.	N.A.

Table 4. Key findings of included articles (continued)

Author , year	On- and –off-road bicycling/ walking trails	BEICs affecting total infrastructural system	Overall PA	Walking	Bicycling	Walking and bicycling / Active commuting	SB
Rissel et al., 2015 [73]; Crane et al. 2017 [68]	•		N.A.	N.A.	Number of cyclists increased with 23% and 97% at two points at the trail, compared to 3% in the whole city at follow-up I. At follow-up II, the number of cyclists increased by 0.9% and 6.4% from baseline, in contrast to a -2.0% reduction in bike counts across Sidney city council. Weekly frequency of cycling did not change over time at follow-up I. Participants in the intervention group reported a higher frequency of cycling compared with the control group, at follow-up II. Cyclists living between 1.00-2.99 km away from the intervention area increased minutes of cycling per week compared with cyclists living further away (>3km). MVPA did not significantly change for one of the groups. At follow-up I, travel to work or study by bicycle decreased in all groups. No difference between intervention and control area. At follow-up II, travel to work was not reported.	N.A.	N.A.
Parker et al., 2011 [79]	•		N.A.	N.A.	Number of cyclists per day increased after intervention.	N.A.	N.A.

Table 4. Key findings of included articles (continued)

Author , year	On- and –off-road bicycling/ walking trails	BEICs affecting total infrastructural system	Overall PA	Walking	Bicycling	Walking and bicycling / Active commuting	SB
Parker et al., 2013 [72]	•		N.A.	N.A.	Increase of cyclists on all streets. The number of cyclists increased on intervention streets but decreased on adjacent side streets.	N.A.	N.A.
Pazin et al., 2016 [80]	•		No change in moderate-to-vigorous leisure time PA in any exposure group. Walking + leisure time MVPA increased among individuals living closest to the intervention area, but not for those living further away.	General increase of walking and a higher weekly volume of walking at follow-up among residents up to 500 m from the new route compared to those living further away. Leisure-time walking increased by 32 min/week among residents living up to 500 m from the new walking and cycling route, while remained stable in groups further away from the intervention area.	N.A.	N.A.	N.A.
West et al., 2011 [81]	•		On average, number of days participating in MPA and VPA increased (significance not reported). No significant interactions between intervention and proximity for MPA and VPA.	Walking increased after intervention (significance not reported). No significant interaction between intervention and proximity.	N.A.	N.A.	N.A.

Table 4. Key findings of included articles (continued)

Author , year	On- and –off-road bicycling/ walking trails	BEICs affecting total infrastructural system	Overall PA	Walking	Bicycling	Walking and bicycling / Active commuting	SB
West et al., 2015 [82]	•		MPA and VPA did not change over time. No significant interaction between residential proximity to the intervention and greenway development for MPA or VPA.	Days of walking did not change over time.	N.A.	N.A.	N.A.
Goodman et al., 2014 [65]; Song et al., 2017 [74]; Panter et al., 2017 [67]		•	At follow-up I, mean levels of MVPA (other than walking/ cycling) declined. No proximity effect for PA outcomes. At follow-up II, mean levels of MVPA (other than walking/ cycling) declined over time. Proximity to the intervention was associated with increased total PA, but not with MVPA other than walking and cycling.	Median total time spent walking decreased between baseline and follow-up. Participants living closer to the intervention were more likely to take up walking for transport. Proximity to the intervention was not associated with total walking or walking for recreation.	N.A.	At follow-up I, Mean levels of walking and cycling for transport and recreation did not change. No proximity effect for total walking and cycling was detected. At follow-up II, mean levels of walking and cycling for transport and recreation did not change. Individuals living closer to the intervention area reported increases in walking and cycling, relative to those living farther away. Proximity to the intervention was not associated with a modal shift from motorized to active transportation. Use was associated with a modal shift from motorized to active transport.	N.A.

Table 4. Key findings of included articles (continued)

Author , year	On- and –off-road bicycling/ walking trails	BEICs affecting total infrastructural system	Overall PA	Walking	Bicycling	Walking and bicycling / Active commuting	SB
Heinen et al., 2015 [70]; Heinen et al., 2017 [66]; Panter et al., 2016 [71]		•	Total physical activity and total recreational PA did not change over time. No exposure effect on recreational or overall PA	Minutes of cycling per week declined over time. Exposure to the busway was associated with a significantly greater likelihood of an increase in weekly cycle commuting. Walking on the commute and for recreation did not significantly change over time. No exposure effect on walking.	N.A.	In maximally adjusted models, proximity predicted a large increase in active travel mode share and reduced the likelihood of a small decrease in active travel mode. No significant association between level of exposure to the intervention and specific modal shifts or the belonging to a group that showed a full or partial modal shift. Time spent in active commuting decreased over time. Exposure to the busway was not associated with combined walking and cycling.	N.A.
Hirsch et al., 2017 [77]		•	N.A	N.A.	Overall percentage of commuting by bicycle increased after implementation of trails. Increases in bicycle commuting restricted to tracts close to the off-road trail system.	N.A.	N.A.
Krizek et al., 2009 [78]		•	N.A.	N.A.	Bicycle mode share increased in the overall sample, but the areas with new cycling facilities showed a larger increase compared to the areas without new cycling facilities.	N.A.	N.A.

DISCUSSION

Main findings

This study systematically reviewed the available literature on the effect of BEICs on PA and AT. In total, 19 articles were included and assessed. We found that the implementation of single on- and off-road bicycling and/or walking trails resulted in inconsistent effects on PA and walking, but predominantly positive effects on bicycling. More extensive BEICs such as the implementation of a bus lane with parallel walking and bicycling trail and traffic-free bridges resulted also in mixed results, predominantly non-significant effects. However, when taking proximity to the intervention into account, bicycling seems to increase after BEICs. None of the studies measured SB. The majority of the studies was designed or executed before the effects of SB on several health outcomes and cardio-metabolic risk became more evident and subsequently gained attention in studies [88]. The current state of evidence emphasizes the need to include SB into future studies. Some undesirable effects were detected as well; four BEICs resulted in decreases in overall PA, bicycling and/or walking and bicycling. Overall, our findings partly support the results of previous systematic reviews [15, 29], but what our review adds is that the effectiveness of BEICs varies greatly across intervention types and types of outcome measure. Not all infrastructural interventions result in positive effects for PA and/or AT. Studies specifically targeting PA and small interventions showed more effects than those addressing more global and drastic infrastructural changes such as the construction of a traffic-free bridges.

When interpreting these results, it is important to consider both the effect of the magnitude of an intervention and the effect of the study quality on the results. The magnitude of the BEICs varied among studies in this review. On- and off-road bicycling and/or walking trails are relatively small interventions, specifically targeting the promotion of PA and AT. On the other hand, more extensive interventions typically imply major changes to whole (infrastructural) systems [49]. This type of BEIC may eventually lead to changes in PA, AT and SB, but also to compensatory adaptive processes and feedback loops that make it harder to assess clear mechanistic pathways and direct effects [89]. Studies evaluating specific behavioral outcomes of extensive interventions may give insights in details at the expense of detecting more general changes in the broader system. Similarly, evaluating specific behavioral outcomes of relatively small interventions, such as bike counting at bike trails, increases the likelihood of finding effects which may reflect a substitution of PA behaviors rather than a change in overall PA.

We also found variation in the total risk of bias in the included studies. As stated, due to the limitations of the assessment tool, the risk of bias assessment was not used to determine

the absolute risk of bias, but to compare the study quality among the included studies. The risk of bias in the studies evaluating on- and off-road walking and/or bicycling trails was generally higher than that in the studies assessing more extensive infrastructural interventions, especially in the domains of outcome measurement bias and bias in the selection of reported results. We found that more recent articles tended to find more non-significant results compared to older articles, while the quality of the articles seems to improve over time. Studies with a higher risk of bias were more likely to report significant changes in outcomes than studies with a lower risk of bias.

In line with Craig's (2012) recommendations, recent studies included in this review mainly reported on extensive BEICs and used more refined and complex study designs, i.e. lower risk of bias [39]. Applying these more refined and complex designs seem to decrease the possibility to detect significant changes in PA and AT. The effectiveness of extensive BEICs on PA and AT might therefore be underestimated compared to studies evaluating the implementation of walking and/or bicycling trails and using simpler and straightforward study designs. Moreover, the results of the more simple and straightforward studies are at greater risk of bias and therefore need to be interpret with caution.

One of the elements that were used to make the designs more refined is the assessment of individual-level exposure to the intervention. Humphreys et al. (2016) described three possible methods to assess exposure to the intervention area whereas the most practical and straightforward one is area-based exposure in which existing administrative spatial boundaries are used to create groups [90]. A more refined method is to create exposure groups based on individually computed proximity to the intervention. The most sophisticated way to create groups based on exposure to BEICs is to assess individually calibrated exposure, which determines whether exposure is likely to occur based on pre-existing behavior. Remarkably, all negative outcomes that were found for BEICs affecting the total infrastructural system were turned into non-significant or even positive effects when proximity was taken into account. This emphasized on the need to measure proximity to the intervention area, especially in complex system changes.

Furthermore, the amount of time between the BEICs and the follow-up measurements might affect the results. Two studies assessing on- and –off road bicycling and/or walking trails had follow-up measurements >12 months after opening of the intervention area and both found solely positive effects on overall PA, walking and bicycling [68, 76, 80]. For BEICs affecting the total infrastructural system, two studies had a follow-up >12 months. Although the outcomes were not consistent, none of the studies with a follow-up time longer than 12 months reported negative results. This confirms previous indications that sufficient time between the BEICs and follow-up measurements are needed [29]. Also, multiple follow-up measurements enable to evaluate behavior changes over time.

Another important factor affecting the quality of studies is the method and protocol used to measure PA and AT. Studies included in this systematic review used questionnaires, systematic observations, electronic bike counts or a combination of accelerometry and GPS to assess PA and AT. Remarkably, all studies reporting counts for bicycling, walking and/or PA found increased overall PA, walking and/or bicycling levels after BEICs. However, three studies did not include a control area in their observations [68, 73, 79], and the other two found decreased PA levels in adjacent streets [72, 76]. This suggests that the interventions led to changes in cycling routes rather than a change in the AT behavior of residents. Individual-level, objective full-day PA measurements would be necessary to test this hypothesis.

Although the use of accelerometry has resulted in better validity and reliability when measuring PA compared to questionnaires, only one study used accelerometers to assess PA [75]. This study found no effect of living in the intervention area on PA, but they only assessed overall daily MVPA. Other researchers have reported that inconsistencies in their findings may be due to measuring PA in only one domain (e.g. overall PA or total MVPA) instead of measuring context-specific PA patterns [91]. Context-specific PA patterns can be defined as daily PA assessed in total and in different domains throughout the day, with context referring to the domain in which behavior occurs. Using context-specific objective measures enables researchers to assess how and where PA or SB behavior takes place and how PA in one domain relates to PA in other domains. It can identify changes in PA or SB behaviors during the day that do not affect total daily PA. In other words, measuring daily PA involves an increased risk of "missing" changes in PA at specific moments in time that are potentially compensated at other moments during the day, as the Activitystat hypothesis suggests [92]. By measuring context-specific PA and SB patterns, it is possible to identify these potentially important changes in behavior while retaining the possibility to assess potential compensation. Current objective PA monitors are limited in terms of their capacity to identify context-specific behaviors. GPS loggers can add valuable information about places and contexts to PA measurements, and the combination of accelerometry and GPS will then help to overcome the limitation of current activity monitors in identifying specific PA and SB behaviors [93, 94].

The context in which infrastructural interventions are delivered and received is also crucial for the ability to explain how the impact of an intervention differs in different settings. In this case, "context" includes any factors which are external to the intervention, but which may obstruct or enhance its effects [95]. To determine the relevance and translatability of

results, researchers should carefully and systematically describe the context in which the intervention was developed, applied and evaluated [96]. In the current review, the variety of contexts in which the infrastructural interventions were delivered and the insufficient ways in which they are described might explain the variance in results [93]. Therefore, future studies should specifically report the context in which BEICs take place. Further, eleven out of fifteen unique interventions took place in the USA and Australia and all three unique interventions in Europe were executed in the UK. Previous research has shown that AT is much more common in Europe than in North America, Australia and the UK [97, 98]. European countries such as Germany, Denmark and The Netherlands are more compact, leading to smaller trip distances, which might be important in the choice between active and passive transportation [98]. The higher prevalence of AT makes it more difficult to detect significant increases in AT as result of BEICs. Therefore, when designing future experiments in these European countries, researchers should consider this complexity and design high quality studies to be able to detect changes in PA, AT and SB behavior.

Strengths and limitations

In this study, we used a systematic strategy to identify eligible articles. The selection process was done by two reviewers separately. Also, this review has focused on the effects of BEICs on PA, AT and SB among adults, rather than including a broad range of interventions in the BE and or social initiatives and a variety of participants, e.g. children and elderly people. A first limitation is that the specificity of the research question led to only a small number of eligible articles. In addition, articles published in transport- journals might not be added to the health-related databases which were searched for this review. This could potentially lead to missing articles. We tried to limit this issue by checking the references of included studies and other relevant systematic reviews.

Further, even though the search focused on infrastructural interventions only, we found a lot of variation in the magnitude, content and context of interventions that may have had an important impact on our results. This underlines the need for a better description of the context in which an intervention was effective or not. Also, outcome measures differed tremendously among the included studies, which made it impossible to compare them directly and to calculate effect sizes.

Finally, the specificity of this review led to the exclusion of public transport interventions such as the implementation of light rails or shared bike systems. There is evidence that public transport interventions can lead to an increase of PA and AT levels [99, 100]. However, motives and barriers to engage in public transport differ from those that are associated with infrastructural changes in that they do not only include physical barriers and perceptual barriers which are found in AT and PA [101], but also service barriers and information barriers [102].

Recommendations

This systematic review has discussed several important factors that influence the quality of quasi-experiments and natural experiments. Lower quality studies may show effects that do not represent actual changes in PA, AT and SB. Although it is challenging and expensive, there is need for high-quality experiments in the future, using objective, context-specific PA measurements. This is necessary to detect changes in PA, AT and SB patterns other than changes in overall PA, AT and SB levels. Also, future studies should consider to not only use multiple groups based on proximity to the intervention, but also to determine individual-level proximity and actual exposure to the intervention (or intervention area), using objective measurements. In addition, the context in which interventions are implemented should be described more in detail to make it possible for researchers and policy makers to determine the relevance and transferability of results to other places and contexts.

Conclusion

This systematic review found that BEICs can lead to changes in overall PA and AT, with the most promising results for bicycling. However, the current state of evidence is inconclusive. Improved understanding of the potential of BEICs to increase PA levels and decrease SB at population level asks for more high-quality, in-depth research, while taking into account the broader system in which the intervention takes place. Even though the quality of quasi-experiments and natural experiments seems to improve over time, the following methodological improvements should be considered when designing a natural experiment: the use of objective context-specific PA, AT and SB measurements, provision of detailed descriptions of the context in which interventions take place, inclusion of multiple groups based on proximity to the intervention, and assessment of individual-level exposure and proximity to the intervention.

APPENDIX

Supplementary file 1

Excluded articles based on abstract screening:

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2

CHAPTER 3

The role of context in evaluation studies: Lessons from a process evaluation of integrating health in urban reconstruction

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ABSTRACT

Studies assessing the effects of the built environment on physical activity and health are inconclusive as the results of these studies vary across time, place and measuring method. However, the contexts in which interventions take place are still minimally defined and described. Therefore, the aim of this paper is to explore and describe the role of context in coproducing an integrated urban reconstruction project and its presumed health effects. In this qualitative, retrospective case study, we empirically reconstructed the processes and explored contextual elements of the planning and implementation phase of a major integrated urban reconstruction project. Data triangulation was reached by combining a literature review, observations and semi-structured interviews with stakeholders. Contextual factors were derived from a thick description and structured using the Context In Complex Interventions (CICI) framework. This paper discusses the role of context and the implications for implementation and evaluation. We identified different forms of context that had a crucial role during the agenda-setting, planning and implementation phase whereby events in the political context were the most prominent. Also, we conclude that the implementation stage of the process poses crucial conditions to achieve the intended outcomes and should be assessed and analysed in Health Impact Assessments (HIAs) and evaluation research. Lastly, we argue that the boundary between the initial program and the context became blurred over time, due to the constant interaction between the project and the context. Hereby, we conclude that the line between intervention and context that is proposed in traditional evaluations is subjective and debatable, and evaluation requires a complex adaptive systems approach, in which intervention, implementation and context are analyzed in interaction.

INTRODUCTION

The relationship between the built environment, physical activity and health is the result of a complex interplay between different variables at various functional and geographical levels. Moreover it is modified by ‘wicked problems’, such as social inclusion, health inequalities, urban regenerations and non-communicable disease prevention [103]. These issues are value-ridden and normatively ambiguous, meaning that they lack a clear consensus on the priority status as a public -and thus policy problem [104]. Most of the changes to the built environment thus are complex interventions or programs consisting of multiple interacting components, targeting several behaviours, and addressing a number of groups or organizational levels with multiple outcomes [105]. As the results of studies assessing the effects of the built environment on physical activity and health vary across time, place and measuring method, evidence is inconclusive [30]. As the complexity and wickedness of this issue in many studies is hardly taken into account, this might be also due to the use of primarily traditional research methods.

Researchers traditionally illustrate the proposed associations between intervention and outcomes as a linear relationship, using a logic model or program theory [106]. This might be useful in conditioned trials, but in practice, it is hardly possible to retrace outcomes and impacts to a single intervention, policy or program as if it was a linear model, given the crucial role of time, context and the interactions between the different components of the complex intervention [107]. In addition, researchers often ignore the complexity of systems in an attempt to understand the effects of changing single elements of a process. Simplifying complex realities into a linear model and thereby ruling out contextual factors or treating them as merely ‘intermediary and confounding factors’ can produce bias and reduce the internal validity of conclusions about correlations and causations, with huge implications for policy or professional action [108]. Existing guidelines for conducting natural experiments emphasize the need to describe and understand the context in which an intervention takes place in order to enhance the validity of the results [39, 109]. However, contexts are still minimally defined and described in published papers [30].

The current article presents an in-depth case study as part of a health impact assessment (HIA) on the effects of a major integrative infrastructural urban redesign project in Maastricht on physical activity and health; the Green Carpet project. In this 1.2 billion euro reconstruction project, a highway that crossed several neighborhoods was tunnelled and the space on top of this tunnel was redesigned and prioritized for pedestrians and cyclists, which is further elaborated on in paragraph 2. The aim of this paper is to explore and describe the role of context in explaining the developments within the integrated urban reconstruction project and its presumed health effects over time, and to draw implications for evaluation theory and methodology such as spatial or urban health impact assessment.

In order to reach the aim of this study, we formulated the following research questions:

1. What project-related contextual factors can be identified, and how can the development of the project be related to elements and developments in context over the course of time?
2. What are the implications of our findings for evaluative research and for comparable integrated infrastructural projects?
3. What are the short-term effects of the project regarding the proposed health-related aims?

To address our research questions, we empirically reconstruct the processes and retrace the influence of contextual elements using an ecological perspective.

PROJECT DESCRIPTION

Setting

The setting of this case study is a medium-sized city of about 120,000 inhabitants in the South-Limburg region of the Netherlands, Maastricht. For over 50 years, the A2 highway crossed several (deprived) neighborhoods in Eastern part of the city (Fig. 1).

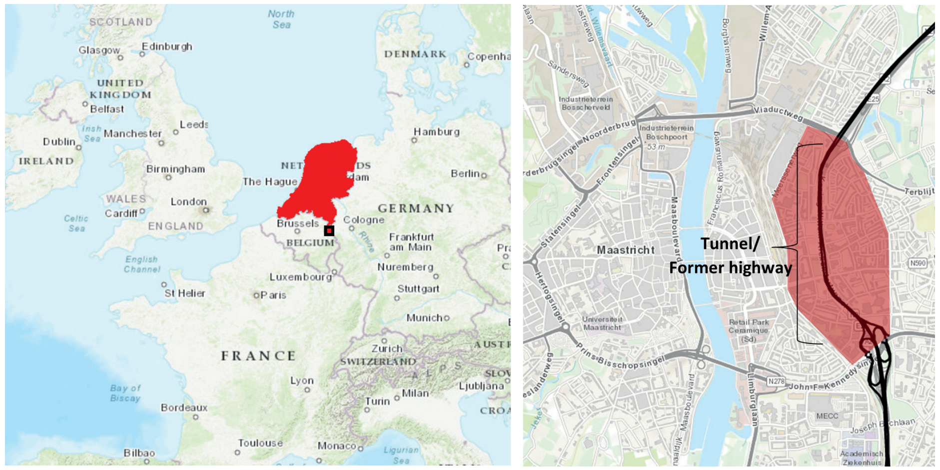

Figure 1. Left: Geographic location of Maastricht (square) in The Netherlands (red); Right: City of Maastricht, A2 highway (black line), crossing the neighborhoods in East Maastricht (red area)

Problem analysis

The ever-increasing levels of air pollution and noise caused by the traffic congestion at the A2 highway, became a threat for the residents in the proximate neighborhoods. In 2010, the annual average concentration nitrogen dioxide was 39 µg/m3, and thereby just below the European norm (European and World Health Organisation (WHO) norm: 40 µg/m3). For particular matter (PM10), the yearly average concentration was 29 µg/m3, which was below the European norm (40 µg/m3), but exceeded the standard of the WHO (20 µg/m3) [35]. Also, the perceived livability levels of the affected areas were alarming. In 2004, five out of seven neighborhoods bordering the highway indicated the traffic nuisance as the largest liveability problem. Also, in three of the neighborhoods bordering the A2 highway, 46% (Nazareth), 53% (Wyckerpoort) and 60% (Wittevrouwenveld) of the inhabitants sometimes felt unsafe in their residential area due to crime and traffic, compared to the average of 36% for the whole city of Maastricht [36].

The project: The Green Carpet

The initial project, politically approved in 2010, consisted of two components; changes in the road infrastructure and area- and real estate development. The formal contracting authority for the project was the A2 Maastricht Project Agency, established in 2003. The total costs of the project is estimated at €1.2 billion, of which €850 million was invested by European (€20 million), national (€680 million), provincial (€54 million), and local (Maastricht: €95 million; Meerssen: €1 million) authorities. The contractor, Avenue2, invested the remaining €757 million.

A double-layered tunnel was constructed to replace the highway and facilitate the (inter) national traffic. The lower tube of the tunnel facilitates the traffic that passes by Maastricht and the upper tube facilitates the traffic destined for Maastricht and surroundings. On top of this tunnel, two one-way streets accommodate the remaining local traffic. The middle part of the profile, prioritized for pedestrians, cyclists and recreation, is separated from the adjacent streets by grass and trees, creating the so-called 'Green Carpet' as shown in Fig. 2. Plan estimates show a reduction of overground traffic of 80% per day [110]. Also, 1100 new dwellings for private and social housing and 30.000m2 of new commercial spaces are planned alongside the Green Carpet. The real estate is currently under construction and should be finished by 2026. In 2018, a multiannual program was proposed, aiming to improve the social environment in the area bordering the new Green Carpet.

Figure 2. Schematic overview of the tunnel and the "Green Carpet" on top of it. Avenue2, (www.a2maastricht.nl)

The proposed and (yet partially) executed plans for the physical environment aimed to affect the inhabitant's health in two ways: the elimination of overground traffic should lead to a better environmental quality regarding air, noise and pollution, and the reconnection of the physical and social structure of the neighborhoods bordering the highway. On the other hand, the design of the Green Carpet on top of the tunnel aimed to increase the use of active transportation, i.e. walking or cycling for transport, and active recreation.

METHODS

Research perspective

This study uses an ecosystems perspective, which presents a holistic approach articulating the complex interactions between humans and their environment. For example, the Social Determinants of Health and Environmental Health Promotion model [111] explains how social, political and economic processes interfere with the built environment to influence population health. To understand these dynamic and partially unpredictable ecosystems, complex system thinking is essential [112]. Complex systems are composed of a diversity of components that interact with each other, affect each other, and thereby generate new behaviour for the system as a whole [23]. Also, the system is constantly adapting to the conditions in time and context.

In this qualitative, retrospective case study, we empirically reconstructed the design processes and explored contextual elements of the agenda-setting, planning and implementation phase of a major integrated urban reconstruction project. Data triangulation was reached by combining a literature review, semi-structured interviews and observations.

Project archive and documents analysis

We searched relevant on- and offline project-related archives and databases for sources with three types of purposes: papers or reports supporting decision- and policy making, reports and minutes of public consultations, and documents evaluating the processes within the project. We excluded documents focusing solely on technical details of the project. In total, 34 relevant documents originating from 1987 until 2019 were included, of which nineteen reports related to decision- and policymaking, and twelve related to public consultations or co-design sessions. Three sources were evaluations of the project. The majority of the documents is public available and written by local, regional or national governments.

Semi-structured interviews

To gather contextual information about the collected literature, interviews were held with stakeholders, until data saturation. We first interviewed a key informant, after which we applied a snowballing method as recruitment strategy whereby we aimed for a maximum diversity of included stakeholders. In total, nine individuals were interviewed between April 2018 and May 2019. Their characteristics are presented in Table 1.

Table 1. Respondents' characteristics

Respondent	Position	Role
R1	Director	Project management
R2	Area manager	Project management
R3	Pastor	Representative of the inhabitants
R4	Member A2 Neighborhood Platform	Representative of the inhabitants
R5	Chair A2 Neighborhood Platform	Representative of the inhabitants
R6	Health scientist municipality health services	Health- and/or societal advisor
R7	Member political working group A2	Representative of the inhabitants/ political parties
R8	Manager social domain municipality	Health- and/or societal advisor
R9	Environmental scientist municipality health services	Health- and/or societal advisor

The interviewer used a topic list covering the key moments, decisions or events that were identified in the document analysis (Supplementary material, table S1). As we aimed to gather information about the broader context of the project, the interviews had an open character to maximize the scope of respondents' experiences and observations.

Observations

Between April 2018 and February 2019, four meetings of the A2 Maastricht Project Agency with stakeholders in the area were observed: the opening of the Green Carpet with inhabitants of the affected area; meetings of the A2 Maastricht Project Agency with community and area managers of the municipality of Maastricht, and a meeting of the A2 Maastricht Project Agency with council members of the municipality. Primary goal of the observations was to map the relationships between stakeholders, sense the general atmosphere of interactions between them, and validate the impressions about the general interpretation of the project that we derived from the interviews and the literature review. We registered attendees, the aim and outcomes of the meeting, alongside attendees' general attitudes towards the projects and other stakeholders, as perceived by the observer.

Analysis

For the analysis, we used an iterative approach. First, all collected data was synthesized into a thick description, including factual information and clarifying quotes, which was member-checked by key interviewees. This thick description was used to empirically reconstruct the processes by structuring the data in a chronological manner, resulting in a timeline with key moments during the process. Next, we performed an inductive analysis, which revealed the importance of contextual factors in shaping the project and its implementation. Consequently, we deductively used Context and Implementation of Complex Interventions (CICI) framework to identify and structure the different forms of context that played a role during the planning and implementation phases [113]. The CICI framework comprises three dimensions; context, implementation and setting. The framework describes seven domains of context: the geographical, epidemiological, socio-economic, socio-cultural, political, legal and ethical context (Table 2).

Table 2. Domains of context as described in the CICI framework (Pfadenhauer et al., 2017)

Context domain	Description
Geographical	Refers to the broader physical environment, landscapes and resources, both natural and transformed by humans (e.g., infrastructure), available in a given setting.
Epidemiological	Refers to the distribution of diseases or conditions, the attributable burden of disease, as well as determinants of needs in populations, including demographics. Also psychosocial and physical needs of individuals would fall into this category.
Socio-cultural	Comprises explicit and implicit behaviour patterns, including their embodiment in symbols and artefacts. It refers to the conditions in which people are born, grow, live work and age and social roles. Constructs such as knowledge, beliefs, conceptions, customs, institutions and any other capabilities and habits acquired by a group are included in this domain.
Socio-economic	Comprises the social and economic resource of a community and the access of a population to these resources.
Ethical	Comprises reflections of morality, which encompasses norms, rules, standards of conduct and principles that guide the decisions and behaviour of individuals and institutions.
Legal	Concerned with the rules and regulations that have been established to protect a population's rights and societal interest.
Political	Focuses on the distribution of power, assets and interest within a population, as well as the range of organizations involved, their interests and the formal and informal rules that govern interactions between them.

3

Finally, we used an analysis grid to further analyze the identified contextual elements arising from the literature review and stakeholder interviews (Table 3). The people involved in the analyses were part of a multidisciplinary team consisting of researchers in the (public) health- and social sciences, and in the policy- and public administration domain.

Table 3. Analysis grid

	Geographical	Epidemiological	Socio-cultural	Socio-economic	Ethical	Legal	Political
Project management							
Health and liveability							
Citizen participation							

RESULTS

In this section, we describe the key decisive moments in the historical path of the A2 reconstruction trajectory. Table 4 summarizes these key moments, which are then elaborated on in the text below.

Description of the historical path of the project

Start of the traffic congestion

After the opening of the highway A2 passage in Maastricht in 1959, the congestion rapidly increased due to the fast industrialization and associated increase of car use. Local politics started to acknowledge the problems caused by the A2 highway, crossing the deprived neighborhoods in East Maastricht. Between 1979 and 1998, the municipality of Maastricht initiated the first attempts to put the A2 highway in Maastricht on the national agenda. However, due to insufficient budget (1979) and reprioritization of available funds (1998) of the national government, both attempts failed.

Table 4. Formal and informal key moments during the planning and execution phases

Date	Event
1979 – 1998	Two failed attempts of getting highway A2 on national political agenda
2001	Publication of rapport 'Maastricht raakt de weg kwijt' ('Maastricht looses track') (Aveco-deBondt, 2001)
	Research confirms poor air quality in Maastricht and in schools near A2 highway
2002	National politician video recorded commitment to A2 reconstruction reminded by Maastricht mayor during national election campaign
2003	Management agreement between national, provincial and local governments in mandated A2 Maastricht Project Agency
	Municipal council A2 committee for political decision-making preparations
2009	Voluntary consultation of the public during tender procedure
2010	Gentlemen's agreement between A2 Maastricht Project Agency and A2 Neighborhoods Platform
2012	Aggregation of communication teams and budgets of A2 Maastricht Project Agency and construction agent Avenue 2
2014 - 2017	Co-design sessions with stakeholders about i.a. 'City Center Development Maastricht East', and 'Health & The Green Carpet'.
2015	Publication action program 'My Healthy Green Carpet 2030'
2018	Publication 'Social Agenda Green Carpet' and publication proposal multiannual social program
2019	Publication first report on short-term effects on noise and air quality in the affected area.

'Maastricht Looses Track'

In 2001, the municipalities of Maastricht and Meerssen, the province of Limburg and Rijkswaterstaat published the rapport "Maastricht Looses Tracks" ("Maastricht Raakt de Weg Kwijt") [114], which was used for negotiations with the national government. As the traffic issues by themselves were not as severe as in other parts of the Netherlands, once more risking national government denial of the proposal, the authors added the liveability issues for neighbouring residents as an additional dramatic dimension, as this quote from a key player illustrates:

It turned out that, in relation to the traffic congestion in the conurbation of Western Holland, the traffic congestion in Maastricht was actually not too bad, but thereby you can be easily denied by national politics. [...] We thereafter defined it as a social issue [...] in terms of traffic safety, air pollution, noise disturbance. Then you raise the issue really above the parapet and then you broaden it to a livability issue [...] and then you have to dramatize in a good way, that it is about people and their direct pleasure in life (R2, 03-04-2018).

Investigating school children's health

In the same year, research of Maastricht University published a report on air quality and health that showed that children in schools next to the highway had more health issues compared to children in other schools. These results were presented to the Minister of Traffic and Waterways during a working visit to Maastricht, to confront her with the severity of the situation.

Political confrontation during national election campaign

During the campaign for the national Parliament elections in 2002, the City Council of Maastricht invited all national party leaders to speak out on the situation in Maastricht. All party leaders called for action. Their statements were videotaped and later, when the government had to cut on expenses and threatened to cancel the A2 Project again, the mayor of Maastricht, a former Christian-Democrat Member of Parliament confronted the personal-acquainted Christian-Democrat Prime Minister on national television with his commitment statement, and thereby increased the political pressure on the Dutch government. Hereby, the former mayor of Maastricht played high stakes and deliberately put his good relationship with the Prime Minister at risk.

A2 Maastricht project agency

In 2003, the public parties involved in the project, the Ministry of Transport, Public Works and Water Management, Province of Limburg and the municipalities of Maastricht and Meerssen merged the various developments (i.e. traffic problems, accessibility of the city and (environmental) quality of the neighborhoods along the A2 passage), into one integral project and established the A2 Maastricht Project Agency. They had a far-reaching mandate to be able to make decisions commissioned by the represented parties, without the constant interference of local, regional or national politics, and at the same time carefully prepare the contents of non-mandated political decisions. In respect of the integral approach, all parties had equal power within the A2 Maastricht Project Agency, leading to depillarization of the government, illustrated by the following quote of one of the interviewees:

"The money of [the ministry of] Traffic and Waterways, is meant for asphalting national highways. [...] But then the Ministry [of Traffic and Waterways] says: 'Wait a moment. We give A2 Maastricht lot of money, but a part of this money is used for urban renewal. That is something the Ministry of Housing, Spatial Planning and the Environment should be doing'. Then you will never get there. You want people to think beyond their sectoral scope, and that's what the Ministry of Traffic and Waterways ultimately did through integral thinking and generating social added value". (R1, 14-06-2018)

Municipal council A2 committee

During the planning phase, the municipality of Maastricht set up a workgroup, consisting of elected City Councillors, which prepared political issues with the right priority and context when presented to the full Council, facilitating a more smooth political decision-making process. As a result, both the infrastructural and the area development plans did not lead to political motions and later on, the license application procedures went faster than usual.

A2 neighborhoods platform

After the public parties signed the first management agreement in 2003, the A2 neighbouring residents felt neglected by them. The individual neighborhoods had separate consultations with the municipality, leading to different opinions and poor communication between the municipality and the residents. Two Council members proposed a joint neighborhood platform including representatives of all affected neighborhoods in the A2 area: the A2 Neighborhoods Platform. Members of the platform brought input from their own neighborhoods to the platform's meetings. Next to internal meetings, consultations with the A2 Maastricht Project Agency and contractor Avenue2 were organized to address the problems in the affected neighborhoods. However, conflicting opinions within the A2 Neighborhoods Platform led to the municipality ignoring their opinions during the start of the planning process, as exemplified by one of the respondents:

"Because they [municipality of Maastricht] said; those [opinions of the] neighborhoods are divergent, so let us just decide whether it will be a road bypass or tunnel based on our own knowledge." (R5, 11-1-2019)

To strengthen the political position of the platform, the most important rule within the platform became that they always carried out one opinion on each topic.

Voluntary consultation of the public during tender procedure

In 2009, the A2 Maastricht Project Agency arranged a voluntary consultation to involve the public during the tender procedure. Three market parties presented their infrastructural and area development plans. About 3600 individuals visited the consultation sessions, of which 240 persons and 21 organizations reacted on the plans. Based on these reactions, no additional formal requirements were added to the framework for the plan, but the parties were asked to pay extra attention to the most mentioned discussion points: air quality, sustainability and traffic flow at the neighborhood level. These points were not legally binding, but were addressed during the final decision making for one of the parties. The A2 Maastricht Project Agency mentioned that the consultations resulted in a limited amount of official legal appeals during the formal procedures of which none of them turned out to be admissible or founded, which saved time and money for the public parties and contractor.

A Gentlemen's agreement

Prior to the implementation of the project, the A2 Neighborhood Platform felt unheard about various topics, such as the amount of traffic in the neighborhoods during the constructions and placement of noise barriers. The formal step to legally challenge these issues was to start a procedure at Council of State. However, the A2 Maastricht Project Agency expressed their strong position in these procedures and the small chance of success for the A2 Neighborhoods Platform. Also, the start of an official procedure would result in delays for the A2 Maastricht Project Agency. Therefore, the A2 Neighborhood Platform and A2 Maastricht Project Agency concluded a "Gentlemen's Agreement". Using this informal agreement, the two parties made working arrangements about the concerned topics. The A2 Maastricht Project Agency fulfilled this commitment and the A2 Neighborhoods Platform managed e.g. the realization of noise barriers and additional bicycle crossings.

Communication strategies

In 2012, contractor Avenue2 and A2 Maastricht Project Agency merged their communication budgets and teams, which resulted in a total communication budget of €7.5 million, about 1% of the total investment. Besides the financial benefits, the joint communication team provided a central point were inhabitants could get information, and communicate complaints or comments.

The joint communication team started with the provision of online and offline information. In addition, three A2 “stewards” were hired, who walked around in the affected neighborhoods to provide information, collect questions from inhabitants, distribute flyers and information folders, solve small problems, make pictures and to give tours. Earlier, a damage registration center and service line East Maastricht was established. The damage control center informed residents who considered going to court, claiming damage incurred by the A2 project or constructions, about the success rate of their case, aiming to prevent unnecessary costs for legal processes that were not feasible. The damage registration center was active between 2011 and 2016, and received about 300 request. The service line East Maastricht served as a central reporting point for questions and complaints about the project. The service line was active until 2018 and between 2011 and 2016, >6600 questions, complaints and notifications were received and answered.

Co-design sessions

In 2014, A2 Maastricht Project Agency and Avenue2 started with a new form of stakeholder participation in area development: co-design sessions. Co-design sessions are a form of participation in which creative forms of collaboration are used to interact with relevant stakeholders. The outcomes of these co-design sessions differed; some led to new negotiations between the municipality and entrepreneurs, eventually resulting in a new-built supermarket. Two co-design sessions focused on the theme health, but although employees of the municipality health services acknowledged that health became a more emerging theme after these sessions, no concrete plans or arrangements were formed, as illustrated in the quote below:

“I think that the A2 Maastricht Project Agency hoped that [...] everybody would stand up and say: we are going to manage this. [...]. The only thing we have seen hereafter is that health became a more emerging theme during the planning phase. [...] So, there is a change going on in which health in the physical environment get more and more attention, but whether this after the co-design sessions became concrete? No idea.”(R6, 12-06-2018)

This observation was acknowledged by one of the A2 Neighborhoods Platform members:

“They have organized wonderful days, with a lot of stakeholders. But if you see where we ended up with, than that is very little. If you think: ‘I’ll use the outcome of the session just as input and don’t do anything other with it’, then just do not organize it.” (R4, 15-03-2019)

‘My Healthy Green Carpet 2030’

Although the physical barrier between the neighborhoods bordering the A2 neighborhood was removed by opening the tunnel, the risk that the social barrier and associated health inequalities between the low and higher SES neighborhoods keep existing remains. The reports of the National Institute for Public Health and the Environment (RIVM), Smart & Healthy City and Space & Health offered national policy-based opportunities to explicitly articulate the theme health in relation to the project, as mentioned by one of the respondents [115, 116]:

“I read about ‘Smart City’ and ‘Healthy City’, so I started to delve into it. I thought; this will be the magnet that can group many themes. Then I found out: nobody can ignore the theme ‘health’. (R2, 03-04-2018)

Following these national policy documents, the A2 Maastricht Project Agency initiated and published the Action Program ‘My Healthy Green Carpet 2030’ [37]. The action program included eleven actions to reach technical and social sustainability. The A2 Maastricht Project Agency received a working budget of 3.0 million euro to start the activities described in the action program. This budget was granted to the A2 Maastricht Project Agency by the national government, based on the positive results of the A2 Maastricht Project regarding planning, budget and collaboration between the involved parties.

Societal agenda green carpet

The Societal Agenda Green Carpet followed from the action program ‘My Healthy Green Carpet 2030’. It proposed a multiannual programmatic approach aiming to improve the social environment in the area bordering the new Green Carpet. To collect topics for the agenda, three independent persons with various personal backgrounds visited the area for three months and listened to residents, small business owners and social entrepreneurs to collect wishes, ideas and opinions about the social environment in the neighborhoods. This resulted in a longlist of 20 agenda points [117].

Report on noise and air quality

In November 2019, the Atlas Living Environment of the Dutch government presented the first effects of the project on noise and air quality. In 2017, the amount of noise was reduced with about 5 to 20 dB. The amount of nitrogen and particular matter decreased from 25 to 39 µg/m3 to <25 µg/m3 and 13–14 µg/m3 to 11–12 µg/m3, respectively (Figure 3).

Figure 3. Nitrogen dioxide concentrations in the affected area (boxes), before the opening of the tunnel in 2015 (left) and after the opening in 2017 (right). *Atlas* Living Environment, (https://www.atlasleefomgeving.nl)

Analysis of contextual factors

In this paragraph, we analyze to which extent which types of context have influenced the initial project. Here, the context includes all factors external to the project or involved stakeholders. The contextual elements emerging from the historical path analysis are structured according to the analysis grid (Table 5). Italics are used for the elements for which we could not establish a direct link, but that were identified as potentially influencing the project or implementation process. Lastly, we will elaborate on emerging elements of the project, which were proposed and implemented by the A2 Maastricht Project Agency, and which were not clearly definable as a factor in the context.

Geographical context

The geographical context influenced the planning procedure, due to the physical location of the city of Maastricht. Maastricht is bordered by protected natural areas on the East and West side of the city. Although consultations with the public led to the exploration of a Western ring road, the alternatives of an Eastern or Western ring road were both rejected based on the impact of a highway on these natural sites and protected species living there [118]. Consequently, a tunnel on the former trajectory was the best possible option.

Table 5. Analysis of contextual elements emerging from the historical path analysis

	Geographical	Epidemiological	Socio-cultural	Socio-economic	Ethical	Legal	Political
General	Physical location of the city						Confrontation during national election campaign
Health and livability		Investigating school children's health	*Number of people using municipal social services.*	My Healthy Green Carpet 2030 Societal Agenda Green Carpet	*My Healthy Green Carpet 2030* *Societal Agenda Green Carpet*		Investigating school children's health Reports 'Ruimte & Gezondheid' and 'Slimme & Gezonde Stad' My Healthy Green Carpet 2030
Citizen participation			*'anti-governmental' sentiment*		*Voluntary consultations of the public*		*Voluntary consultations of the public* *Co-design sessions*

3

Epidemiological context
The poor air quality in Maastricht and its associated health risks were used to dramatize the Maastricht case, in order to draw attention to this region. As the traffic congestion issues were not as bad compared to other parts of the Netherlands, these environmental health issues in the epidemiological context were used to put the highway A2 on the national agenda. Hereby, the A2 Maastricht changed from a purely traffic-related plan, to an integrated urban reconstruction project, including traffic and livability goal settings.

Socio-cultural context
For many generations, South-Limburg inhabitants lived in an environment in which the manufacturing/mining industry, the Dutch state and the Catholic Church controlled their lives as they provided income and prescribed the rules to which the people had to live. Researchers suggest that this resulted in a passive and dependent culture, with individuals that lack self-management skills [1]. This is supported by e.g. the number of people that make use of municipal social services, which is higher in this region compared to other regions in the Netherlands [119]. The passive and dependent attitude towards these problems created feelings of inferiority among a part of the inhabitants that manifests itself in an 'anti-governmental' sentiment, reflected by the high percentage of people that usually votes for anti-government parties during local or national elections [120]. In this perspective, the various forms of public participation during the project might have taken place to prevent protests against the project, but we found no evidence for this as it was not explicitly expressed by interviewees or described in the included documents.

Socio-economic context
Before the start of the A2 Maastricht Project, the socio-economic status (SES) of the neighborhoods bordering the A2 Highway, was lower than the average SES in Maastricht. This determined the approach during the agenda setting stage, by stressing the need for change in this area as described in the epidemiological context. Later on, stakeholders agreed that to improve the quality of life in these areas, the A2 Maastricht Project should include more than just infrastructural and area developmental plans. In this light, the action program 'My Healthy Green Carpet 2030' was launched, of which the Social Agenda Green Carpet was one of the main results at this point in time.

Ethical context
The voluntary consultations during the planning phase, the extensive communication plan and the emergence of the 'My healthy Green Carpet 2030' might be interpreted as the result of discussions regarding the ethical responsibility of the A2 Maastricht Project Agency in the affected area. The people living in this area first experienced decades of traffic congestion, and later about six years of nuisance during the construction of the

tunnel. However, based on the gathered data, we were not able to distinguish whether these arrangements were implemented due to ethical considerations or that they were primary implemented to save time and money by ensuring a smooth process.

Legal context
The formal procedures during the planning phase of the project were carried out within the stated legal frameworks, and thereby the legal context shaped the project. Although the municipality started working on the upcoming Environment and Planning Act, which revises environment- and planning laws, the A2 Maastricht Project Agency indicated this upcoming change did not influence the planning and implementation of the project. Hereby, we found no evidence that the legal context changed over time, nor that a possible change in the legal context led to changes in the intervention over time.

Political context
As described in paragraph 1.1, the definition of the political context describes four elements: 1) the distribution of power, 2) assets, 3) interests within a population and a range of organizations involved, and 4) formal and informal rules that govern interaction between them. We will categorize the contextual political factors in the paragraphs below.

A defining event in the agenda-setting stage was the confrontation of the Prime Minister with his commitment statement on national television, by the former mayor of Maastricht. This radical move by the Maastricht mayor, in combination with i.a. the alarming research evidence in the Maastricht University schoolchildren study, made sure the A2 Maastricht project was not rejected once more. Although this is clearly an element of the political context, it cannot be classified in one of the four described elements of political context (i.e. distribution of power, assets, interest within a population, and formal and informal rules), as it is a form of political agency.

Also, throughout the project, the focus on health protecting indicators switched to a more complete view on health, including both health protecting and health promoting indicators. The reports 'Ruimte & Gezondheid' (in English 'Space & Health') and 'Slimme & Gezonde Stad' (in English: Smart & Healthy City), created momentum for the A2 Maastricht Project Agency to initiate the action program 'My Healthy Green Carpet', aiming for technical and social sustainability of the project. The action to mobilize (health) resources to create momentum can also be categorized as political agency.

Emergent elements of the project
Some changes to the initial project were proposed by the A2 Maastricht Project Agency itself and we were not able to distinguish whether this was an internal or contextual factor. We will illustrate this with the following four key moments.

The A2 Maastricht Project Agency experimented with a depillared, integrative project approach that forced the public partners to collaborate, resulting in shared responsibilities and implementation power. The far-reaching mandate of the A2 Maastricht Project Agency was one of the factors that ensured that the construction of the tunnel and Green Carpet went according to plan and within budget, which later persuaded the national government to finance the preliminary research and implementation of the action program 'My Healthy Green Carpet 2030'. This element might be categorized as a decision in the political context regarding formal rules and the distribution of power.

Secondly, the establishment of both the A2 Neighborhoods Platform as the political A2 workgroup resulted in more support among politicians and inhabitants. The A2 Neighborhoods Platform managed to implement some of their ideas during the construction phase, such as the installation of the direct telephone Service Line and earlier realization of temporary pedestrian bridges. The work of the political A2 workgroup did not require demonstrable changes in the project, but resulted in smooth processes in the City Council. Both can be categorized as elements of the (re)distribution of power and might have arisen from contextual influences, but we were not able to separate the internal and external factors.

Thirdly, the extensive communication plan and the legal and voluntary public consultations can be seen as political instruments to gain the support of stakeholders. The consultations evoked many reactions of the public, but there were hardly any legal objections and there were no significant changes to the project. However, the arrangements changed the way of communicating with the public, which in turn might have been a political contextual factor contributing to more public engagement and a smoother process.

Lastly, The "Gentlemen's Agreement" that was concluded between public parties in the A2 Maastricht Project Agency and the A2 Neighborhood Platform resulted in practical changes in the project, and a greater support for the project among the A2 Neighborhoods Platform. Although this element of political agency was an internal arrangement, it was proposed to decrease the social turbulence that the project caused in the affected neighborhoods which in turn is a contextual factor influencing the implementation process.

DISCUSSION

This paper described an integrative urban reconstruction project that in the course of the fifteen-year process evolved from physical urban redesign to the inclusion of social design elements under the influence of its context. The aim was to explore and describe the role of context in coproducing the project and its presumed health outcomes, of which a preliminary evaluation showed promising results regarding various health-related outcomes, such as noise and air quality. In the following paragraphs, we offer three implications for research and practice resulting from the analysis, which we will discuss consecutively.

Role of context in shaping the project
The analysis of key moments showed that the initial project design changed over the course of time. However, as the project progressed, it became increasingly difficult to distinguish the project from its context due to the increasing interaction between the context and the implementation. Especially for the political arrangements, it was virtually impossible to categorize events as internal or contextual factors. This is illustrated by the number of emergent elements of the interventions, which were not initially designed, but evolved from interactions between the project and the context. For example, the A2 Neighborhoods Platform was an internal initiative by two council members and the A2 Maastricht Project Agency, but it arose from public concern within the affected neighborhoods. These concerns made the A2 Neighborhoods Platform a crucial condition to the achievement of the project. In addition, many of the contextual factors were interrelated. For example, the socio-cultural background of the inhabitants of the South-Limburg region affects the political choices people make and thereby might affect the implementation conditions of the project.

While the legal framework shaped the initial project, the political context evoked most of the changes during the planning and implementation phases. Some of the arrangements led to actual changes to the initial project that might affect health outcomes, e.g. the construction of an additional noise barrier. Other arrangements have created favourable implementation conditions, such as the Gentlemen's Agreement that won the support of the residents and kept them from entering long-term legal procedures in the Council of State that might severely obstruct progress. This is in line with findings in similar studies [121] and underlines the assumptions stated in ecological frameworks, which argue the importance of these contexts [17].

Implications for implementation

The importance of the implementation stage is that the initial project has been adapted and revised in such ways that it is much more robust to the feasibility, acceptability and use of the project and thus more capable of achieving the intended impacts. In other words, denying the setting-specific context when implementing public health projects might turnout in a classic case of 'operation successful, patient deceased'. So, adaption of the implementation of the project to its context is crucial to achieving the intended outcomes.

Implication for evaluation

The interactions between two or more contexts makes it impossible to assign process developments and project changes to solely one type of context. This relates to complex adaptive systems theory, in which it is proposed that a system is constantly adapting to the conditions in time and context [23]. The constant debates confirm our suggestion that the proposed distinction between intervention and context, presented in classical evaluations and Health Impact Assessments (HIAs), is debatable and highly subjective. Usually, there is no attention for interactions between the (proposed) project and its context, between contexts or for non-linearity in quantitative study designs. This introduces great uncertainties in such assessments. For practice, this implies that HIAs might be more suitable as a paradigm exploring the possible impacts of comparable integrative projects, rather than a method to estimate absolute effects [122]. In evaluation, it is essential to understand these constant interactions between and within the intervention, implementation and context. This requires a complex adaptive systems approach, in which intervention, implementation and context are analysed in interaction.

The CICI framework was helpful in recognizing the different forms of context that are crucial in a specific case. However, we also faced some limitations using this framework. The definition of the political context was too limited to categorize some of the key moments during the process. Therefore, we recommend adding 'political agency', i.e. the property or capacity of stakeholders to bring something about, to the definition of political context in the CICI framework, to be able to include information about the political game that turned out to be key in the agenda-setting, planning and implementation stages. Also, we recommend adding room for interaction between the different forms of context to the CICI framework.

Strengths & Limitations

One of the strengths of this study is that it adds to the epidemiological evaluation literature a much deeper understanding of the role of different contextual elements that over the course of time contribute to the impacts and outcomes of intervention

and other types of projects. This understanding in future studies could feed back into theories about the health effects of integrated projects in such a way that it provides additional explanations for the outcomes. Additionally, future studies could develop more methodological guidance on how to investigate the relevant contexts that were previously excluded from study designs.

Although this paper describes the processes of a very specific case, we believe that the results are generalizable to similar integrated reconstruction projects in other countries and regions. The current study clearly showed the interconnection of elements and contexts, and the emerging elements within the intervention due to adaptive management strategies. Previously, Crawford et al. (2010) also approached the spatial planning domain as a complex system, including links with climate change, obesity, economic development and accessible environments [123]. They also advocated for adaptive management and partnerships with industry and the wider community. In addition, the successful deployment of community-engaging arrangements, such as the A2 Neighborhoods Platform and public consultations, was also acknowledged by previous research. For example, Lucas et al. (2003) stated that the level of community ownership and the type of community involvement are relevant to the delivery of projects relating to community planning and neighborhood renewal, as well as the delivery of integrated policy [124]. The multi-actor processes and importance of context are also more generally described and sometimes prescribed in policy sciences across the whole domain. To illustrate, Nilsen, Stahl, Roback & Cairney described the influence of context on policy implementation processes and Bekker et al. argue that the blueprint for HIA must be adjusted for the context in which it is used [121, 125].

A limitation of this study is that we did not interview inhabitants living in the affected area. However, we believe that the reflections of the members of the community platform, politicians and the pastor were representative of the resident population in the surrounding neighborhoods, whereas inhabitants' perspectives were also included through co-design sessions led by other interviewees.

Another limitation is that some of the elements arising from the context were not directly linkable to changes in the project, project implementation or outcomes. However, as these elements arose from the literature review and were acknowledged by the interviewees as important elements, we might assume that these elements impacted on the complex system in which the project was initiated and implemented.

CONCLUSION

Changes in the context of mid- and long-term urban reconstruction projects influence the design and implementation conditions that prove crucial to project achievement. As a result, due to the constant interactions between context and the project, impacts can hardly be ascribed to the initial project. Traditional evaluation designs ignore these process dynamics in order to maintain 'design fidelity'. To improve the internal validity, interpretation and implications of future evaluations, we recommend adopting a complex systems approach and mixed methods designs that enable investigating the interactions between the project and its context. Also, we learned that the implementation stage of a project poses crucial conditions to achieving the intended outcomes, by adapting and revising it in a way that is more robust to the feasibility, acceptability and use of the plan.

APPENDIX

Supplementary table S1. Interview grid of the semi-structured interviews

1. General	
1	What was the initial reason for tackling the A2 highway?
2	The initial project was described in terms of obligatory requirements and additional preferences. One of the requirements was integrality/synergy of the total plan. What exactly is meant by this?
3	Who were responsible for formulating the terms of reference?
4	What was your approach to building support for this integrated approach?
5	How did the integrated approach emerge from the process of interactions and decision-making?
6	On a range from full support to full resistance to this integrated approach, can you indicate the levels of support by different stakeholders and how it evolved throughout the process?
7	Did you or anyone else identify or encounter any pitfalls?
8	How were tasks and responsibilities initially divided, and how did that change throughout the process?
9	Looking back, are there other developments or factors in the context that have influenced the coordination and goal achievement of the project?
2. Health and liveability	
1	When, how and by whom was the theme 'health' included in the plans?
2	What questions, needs and wishes did residents currently express with regard to the living environment in the affected neighbourhoods?
3	Which other organizations, companies and parties are active with regard to the quality of life in these neighbourhoods, with which collaboration might have added value?
3. Citizen Participation	
1	How was citizen participation organised? Is there any consultation still ongoing, following the opening of the Green Carpet and what topics are brought up?
2	How were these processes coordinated and by whom, was there also any self-initiated citizen voice?
3	How do residents/professionals have a voice in the further design of the Green Carpet (until 2026)? If not, why not?
4	Which (knowledge) institutes and organizations are involved with regard to the Green Carpet and Blue Care and what kind of research and data is obtained?

3

Supplementary table S1. Interview grid of the semi-structured interviews (continued)

4. Blue Care & Green Carpet	
1	How was interaction organised between the programs of the Green Carpet and Blue Care and to what outcomes?
2	Which methods are used in both programs to organize coordination with residents and interested organisations?
3	Which arrangements/ methods has Blue Care used at operational and administrative levels to fine tune with the Green Carpet program and other projects in the area?
4	In the progress report on ‘My Healthy Green Carpet 2030’ it is stated that the A2 project should also embrace social development of the area, for example in a possible synergy between Blue Care and the Green Carpet. How did this evolve?
5	Are there any plans of ideas for collaboration in the future?
6	With the launch of the Blue Care pilot, it was indicated that a working group would be set up to develop a future-proof socio-physical infrastructure, with a link to the municipal policy in this area and the “The Green Carpet” project. How did this evolve and why?
7	How does this manifest itself in practice?

CHAPTER 4

Do physical activity friendly neighborhoods affect community members equally? A cross-sectional study

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ABSTRACT

An activity-friendly environment may increase physical activity (PA) levels and decrease sedentary behavior (SB). This study investigated associations between socio-demographic characteristics, health-related quality of life (HRQoL), perceived environment and objectively measured PA outcomes. Socio-demographic characteristics were assessed using a questionnaire and HRQoL was measured using the EQ-5D. The Neighborhood Environment Walkability Scale (NEWS-A) was used to assess the perceived environment. SB, light PA (LPA) and moderate-to-vigorous PA (MVPA) were measured using the Actigraph GT3X+. Data from 622 Dutch adults were used in multivariate linear regression analyses to investigate associations between NEWS-A and PA outcomes. Analyses were controlled for socio-demographic characteristics and HRQoL. The presence of attractive buildings was associated with less SB ($\beta = -0.086$, $p < 0.01$) and more MVPA ($\beta = 0.118$, $p < 0.01$). Presence of destinations within walking distance was also positively associated with MVPA ($\beta = 0.106$, $p < 0.01$). Less crime was associated with less MVPA ($\beta = 0.092$, $p < 0.05$). Interactions between personal and environmental characteristics showed that the absence of PA-hindering characteristics (e.g., heavy traffic) was associated with less SB and more MVPA, but only for residents with problems regarding pain and usual activities. The presence of PA-facilitating characteristics (e.g., aesthetics and destinations) was associated with less SB, more LPA and more MVPA but only for the more advantaged people in society. Results suggest that to reduce health inequalities, it would be more helpful to remove barriers rather than introduce PA facilitating characteristics.

INTRODUCTION

A large body of evidence endorses the effect of socio-economic factors such as educational level, employment and ethnicity on mortality and health [126-129]. Moreover, individuals with a lower socio-economic status (SES) are at increased risk of adopting unhealthy lifestyle behaviors such as insufficient physical activity (PA) and spending too much time sitting [130]. These unhealthy behaviors increase the risk of obesity and other non-communicable diseases [7, 131]. Although insufficient PA levels are seen among all subgroups of society, the likelihood of being obese is higher in disadvantaged individuals [132, 133]. It is suggested that socio-economic health inequalities between advantaged and disadvantaged individuals may be related to the built environment in their neighborhood.

A multi-country study found that residents of low SES neighborhoods had less favorable perceptions of the environment in their neighborhood, compared to residents of high SES neighborhoods [134], which might lead to lower PA levels and less favorable health-outcomes. This stresses the need to augment individual-level interventions targeting the increase of PA with interventions at the environmental, policy and societal levels. When designing population-wide interventions, researchers and policymakers should be aware of the differences between “agentic” prevention strategies, in which individuals must use their personal resources, and “structural” strategies, which work through rigorous changes in the total system [135]. Research suggests that treating high-risk individuals with agentic strategies might actually increase health inequalities because disadvantaged individuals can lack the skills needed to change and sustain healthy behaviors [136]. On the other hand, there is increasing evidence to suggest that structural, whole-population approaches generally reduce inequalities [136].

Hence, the built environment is increasingly being used for structural, population-level interventions aiming to increase PA levels and decrease sedentary behavior (SB). Numerous studies explored the associations between the built environment, PA and SB. For example, the presence of bicycling and/or walking infrastructure, the presence of attractive buildings and mixed land-use were found to be associated with increased PA levels [137-140]. On the other hand, heavy traffic, high crime rates and the presence of physical barriers such as train rails and highways were associated with less PA and more SB [141]. Hereby, built environmental characteristics can be divided into two categories: ones that facilitate PA and ones that hinder PA. The presence of PA-facilitating characteristics and the absence of PA-hindering characteristics potentially lead to more PA and less SB. Changing built environmental characteristics would thus seem to enable increased PA levels, but adverse effects on PA were reported as well [15, 142]. These inconsistencies in the existing literature might be due to varying measuring methods and contexts. An important shortcoming in the current literature is the lack of studies that consider the effect of the built environment on different subgroups in society [15]. It is not clear whether associations between built environment, PA and SB are equitably distributed among advantaged and disadvantaged individuals [15]. As reflected in the hierarchy of walking needs [142], personal characteristics are fundamental when people consider being physically active in their environment. Age, employment, physical functioning and quality of life are some of the factors that contribute to the feasibility of walking. Once individuals experience that it is feasible to walk, then the other layers in the hierarchy become relevant, reflecting characteristics of the built environment.

Therefore, the primary aim of this study was to examine the associations between personal characteristics, perceived environment and objectively measured PA and SB of adults. The secondary aim of this study was to identify possible interactions between perceptions of the built environment and personal characteristics, to assess whether associations between the built environment and PA and SB differ among advantaged and less advantaged groups in society.

MATERIALS AND METHODS

Study Design and Sample

Data were collected between September 2016 and July 2017 in two cities in the South-Limburg region of the Netherlands: Maastricht and Heerlen. Ethical approval for the study protocol was granted by the MUMC+ medical ethical committee (METC 16-4-109). The participants provided signed informed consent. Eligible participants (18 years, able to walk without walking aids) were reached through social media, posters, flyers, advertisements in local and regional newspapers and personalized mailing. Those who were willing to participate could register via the Internet or by telephone and after registration, participants received an information letter. If they decided to take part, participants were contacted by the researchers by phone or e-mail to plan the distribution of study materials. Study materials were distributed from community centers. After completion of the measurements, researchers collected the study materials from the participants' homes.

Physical activity and sedentary behavior

The Actigraph GT3X+ accelerometer was used to assess PA levels and SB. Participants were asked to wear the accelerometer during waking hours for seven consecutive days. The Actigraph was worn at the right hip and was only removed during water activities (e.g., bathing, swimming). Raw vector magnitude (VM) data (30 Hz) were downloaded into

Actilife version 6.11.7 (Actigraph, Pensacola, FL, USA) and aggregated to 10-s epochs. The Choi algorithm was used to identify wear- and non-wear time [143]. A valid day was defined as at least 10 h of wear time and a valid week consisted of at least 5 valid days, which could include weekends [144]. VM cut-off points were used to distinguish between SB (0–200), LPA (201–2691) and MVPA (>2691) [145, 146]. To be able to compare PA levels of our sample with the existing literature, we also calculated SB, LPA and MVPA levels at the vertical axis (VT) using the Freedson 1998 cut-off points [147]. All statistical analyses were performed using the VMpercentage of wear-time spent in SB, LPA or MVPA per day as dependent variable.

Personal characteristics–socio-demographic characteristics and health-related quality of life

Participants reported gender, age, household composition, educational level, work status, ethnicity, length and weight. Self-reported length and weight were used to calculate the body mass index (BMI). The EQ-5D questionnaire was used to assess health-related quality of life (HRQoL) in five domains (mobility, daily activities, self-care, pain/complaints and mood), at three levels (no problems, some problems, severe problems) [148]. For all five domains of the EQ-5D a dichotomous variable was created for experiencing no problems (0) or experiencing any/severe problems (1).

Environmental characteristics

The perceived environment was measured using a variety of subscales of the abbreviated version of the Neighborhood Environment Walkability Scale (NEWS-A). The NEWS-A has shown to be a valid and reliable measure for neighborhood walkability [149]. Translated versions of the NEWS-A have been used in several studies in the Netherlands and Belgium [150, 151]. The following subscales were included in the questionnaire: Access to facilities, aesthetics, infrastructure and safety for walking, traffic hazards, crime, lack of parking spaces, hilliness, and physical barriers. Although all items say something about the activity-friendliness of a neighborhood, we distinguished between "PA facilitating characteristics" or "PA hindering characteristics". All NEWS-A items were scored on a 4-point scale and if necessary, items were recoded in order to create scales in which higher scores reflected a more activity-friendly environment. Scores ranged from 1 (not activity friendly environment) to 4 (very activity friendly environment).

Statistical analyses

Statistical analyses were conducted using SPSS version 23 (IBM Corp., Armonk, NY, USA). Descriptive statistics were used to describe sample characteristics and mean values and standard deviations of socio-demographic characteristics, HRQoL, perceived environment, perceived health, PA and SB. Also, all variables were checked on multicollinearity by assessing the correlation matrix and by calculating the variance inflation factor in SPSS. Both did not indicate problems regarding multicollinearity. Associations between personal characteristics, environmental characteristic, and PA outcomes were explored using multivariate linear regression analyses. To assess the main effects of environmental characteristics on SB, LPA and MVPA, we used a hierarchal regression method with two blocks. The first block contained socio-demographic characteristics and the five domains of HRQoL. The second block contained the items of the NEWS-A. The backward deletion method was used for each block to exclude the least significant variables until all remaining variables were statistically significant ($p<0.05$). Model 1 contains significant personal characteristics and model 2 contains significant personal and environmental characteristics. All analyses were performed using VM PA outcomes. Additional moderation analyses were performed to explore possible interactions between personal and environmental characteristics. First, interaction terms were calculated for each possible interaction between socio-demographic characteristics and HRQoL, and environmental characteristics. All possible interaction terms were individually added to model 2, to identify interactions that contributed significantly to the model, independently of other interaction terms. Next, for each outcome measure (SB, LPA and MVPA), model 2 was augmented by a third block containing the detected significant interaction terms. The backward deletion method was used to exclude the least significant variables, with exception of main effects of significant interaction terms. To interpret detected interactions, we performed stratified analyses on the significant interactions and visualized these findings.

RESULTS

Participants' characteristics

In total, 758 participants were included in this study. Thirty-seven participants (5%) were excluded because of missing questionnaire data and 99 participants (13%) did not provide a valid PA measurement over at least 5 valid days, leaving 622 participants in the final sample. Table 1 presents the characteristics of the participants. The mean BMI-index was 24.9 4.2 kg/m2. Although 99% (n = 616) of the participants did not experience any problems regarding self-care, about 12% (n = 75) experienced problems regarding mobility, 10% (n = 62) reported problems with usual activities and 10% (n = 62) reported experiencing moderate or extreme problems regarding anxiety/depression. Also, 31% (n = 193) reported moderate or extreme problems regarding pain/discomfort.

Table 1. Participants' characteristics.

Socio-demographic characteristics (N=622)	**% / M (±SD)**
Gender (% Males)	46%
Age (years)	57.3 (15.6)
Educational level (% Higher educated)	54%
Work status (% Employed)	48%
Ethnicity (% Western)	98%
Household composition	
without children	76%
with children	24%
Body Mass Index (kg/m2)	24.9 (4.2)
Health-related quality of life (N=622)	
Mobility	
no problems	88%
moderate problems	12%
extreme problems	0%
Self-care	
no problems	99%
moderate problems	1%
extreme problems	<1%
Usual activities	
no problems	90%
moderate problems	10%
extreme problems	<1%
Pain/discomfort	
no problems	69%
moderate problems	30%
extreme problems	1%
Anxiety/depression	
no problems	90%
moderate problems	9%
extreme problems	1%

4

Physical activity levels

The mean weartime of the accelerometers was about 14.5 h per day. Average percentage of the day and mean time (minutes/day) spent in SB, LPA, and MVPA calculated using VM and VT counts are presented in Table 2.

Table 2. Participants' physical activity levels based on vector magntiude (VM) and vertical axis (VT) calculations.

Physical activity levels (N=622)	% (±SD)	Minutes/day (±SD)
Wear time		868.5 (196.0)
Vector magnitude		
% Sedentary behavior	65.4 (7.8)	567.5 (98.1)
% Light physical activity	26.1 (6.2)	227.5 (64.0)
% Moderate-to-vigorous physical activity	8.4 (3.7)	73.4 (34.0)
Vertical axis		
% Sedentary behavior	74.7 (6.2)	647.7 (99.7)
% Light physical activity	19.9 (5.3)	173.4 (53.5)
% Moderate-to-vigorous physical activity	5.5 (4.9)	47.4 (25.7)

Neighborhood Environment Walkability Scale

Table 3 shows the mean scores on the items of the NEWS-A questionnaire. Scores on all items ranged from 1.0 to 4.0, with a higher mean score reflecting a higher perceived activity-friendly environment. Means ranged from 2.0 for the presence of a grass/dirt strip that separates streets and sidewalks, the amount of traffic, and the speed of traffic, to 3.5 for the presence of stores within walking distance.

Table 3. Mean scores (±SD) per item of NEWS questionnaire.

Scale	Variable	M* (±SD)
PA facilitating characteristics		
C – Access to facilities	Stores within walking distance	3.5 (0.7)
	Many places to go within walking distance	3.2 (0.7)
	Easy to walk to transit stop (bus, train)	3.4 (0.7)
E – Infrastructure and safety for walking	Sidewalks and streets separated by parked cars	2.9 (0.6)
	Grass/dirt strip separates streets and sidewalks	2.0 (0.7)
	Lightning at night	3.1 (0.5)
	Walkers and bikes on the streets are seen by people in their homes	3.0 (0.5)
	Presence of crossing aids	2.6 (0.8)
F – Aesthetics	Trees along the streets	3.1 (0.8)
	Interesting things to look at	2.5 (0.7)
	Presence of attractive natural sights	2.6 (0.8)
	Presence of attractive buildings	2.5 (0.8)
PA hindering characteristics		
G – Traffic hazards	Amount of traffic	2.0 (0.7)
	Speed of traffic	2.0 (0.7)
	Drivers exceed posted limits	2.7 (0.8)
H – Crime	High crime rate	2.9 (0.6)
	Crime rate makes it unsafe during the day	3.3 (0.6)
	Crime rate makes it unsafe at night	3.0 (0.7)
I – Lack of parking	Parking is difficult	2.1 (0.8)
K – Hilliness	Hilliness	3.4 (0.6)
L – Physical barriers	Physical barriers	3.4 (0.7)

* All items ranged from 1 to 4, in which a higher score is considered as more PA support.

Associations between SB, LPA, MVPA and Personal and Environmental Characteristics

Table 4 shows the associations between SB, LPA, MVPA, personal (socio-demographic variables and HRQoL) and environmental characteristics. Participants with a higher BMI and participants experiencing any/severe problems with self-care showed more SB compared to participants with a lower BMI and participants without problems regarding self-care. Women, lower educated participants, and participants with children in their household showed less SB compared to men, higher educated participants and participants without children in their household. When controlling for those significant personal characteristics, the presence of attractive buildings in the resident's neighborhood was associated with less SB.

Women, older participants, lower educated participants and participants with children in their household showed more LPA compared to men, younger participants and participants without children in their household. LPA was negatively associated with BMI and problems with self-care, meaning that participants with a higher BMI and any/severe problems regarding self-care showed less

LPA compared to participants with a higher BMI and participants that experience any/severe problems regarding self-care. After controlling for significant personal characteristics, no environmental characteristics were associated with LPA. Being lower educated and experiencing pain/discomfort was associated with more MVPA. Older participants, participants with a higher BMI, experiencing any/severe problems regarding self-care and participants experiencing any/severe problems regarding usual activities were associated with less MVPA. When adding environmental variables to the model, the presence of places to go within walking distance and the presence of attractive buildings in the neighborhood were positively associated with MVPA, while a higher score on perceived crime, indicating less crime, was negatively associated with MVPA.

Interactions between Personal and Environmental Characteristics

For the PA-facilitating characteristics, we found the following significant interactions: household composition x places to go (β = -0.517, p = 0.003), educational level x attractive buildings (β = -0.496, p < 0.001) and usual activities x places to go (β = 0.331, p = 0.029). We did not detect main associations for the presence of shadows on sidewalks (model 2), but we detected an interaction between BMI and shadow on sidewalks (β = -0.842, p = 0.002). The presence of places to go within walking distance was associated with decreased time spent in SB and increased time spent in LPA for participants living in a household with children (β = -0.249, p < 0.01 and β = 0.189, p < 0.05, respectively) and less time spent in SB and more time spent in MVPA for participants experiencing no problems regarding usual activities (β = -0.091, p < 0.05 and β = 0.141, p < 0.01, respectively). The presence of attractive buildings was significantly associated with less SB and more MVPA for higher educated residents (β = -0.216, p <0.001 and β = 0.237, p < 0.001, respectively), but no significant associations were found for LPA nor for lower educated participants. Stratification analyses of significant interactions between personal and PA facilitating environmental characteristics are illustrated in Figure 1.

Table 4. Multivariate linear regression models for SB, LPA and MVPA.

	SB		LPA		MVPA	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
	β	β	β	β	β	β
Personal characteristics						
Gender - female (REF= male)	-.156***	-.154***	.199***	.199***		
Age			.158***	.158***	-.132**	-.141**
Body Mass Index	.182***	.177***	-.179***	-.179***	-.127**	-.115**
Educational level - low (REF= high)	-.182***	-.195***	.139***	.139***	.122**	.120**
Household composition – with child(ren) (REF= no children)	-.139***	-.130**	.184***	.184***		
Self-care - any problems (REF= no problems)	.150***	.150***	-.113**	-.113**	-.104**	-.099*
Usual activities - any problems (REF= no problems)					-.158**	-.160***
Pain - any problems (REF= no problems)					.100*	.102*
Explained variance (R^2)	.143		.150		.078	
Environmental characteristics						
Places to go within walking distance (higher score, more places to go)						.106**
Attractive buildings (higher score, more attractive buildings)		-.086**				.118**
Crime (higher score, less crime)						-.092*
Explained variance (R^2)		.150		.150		.113

REF= reference category; *=p<.05; **=p<.01; ***=p<.001.

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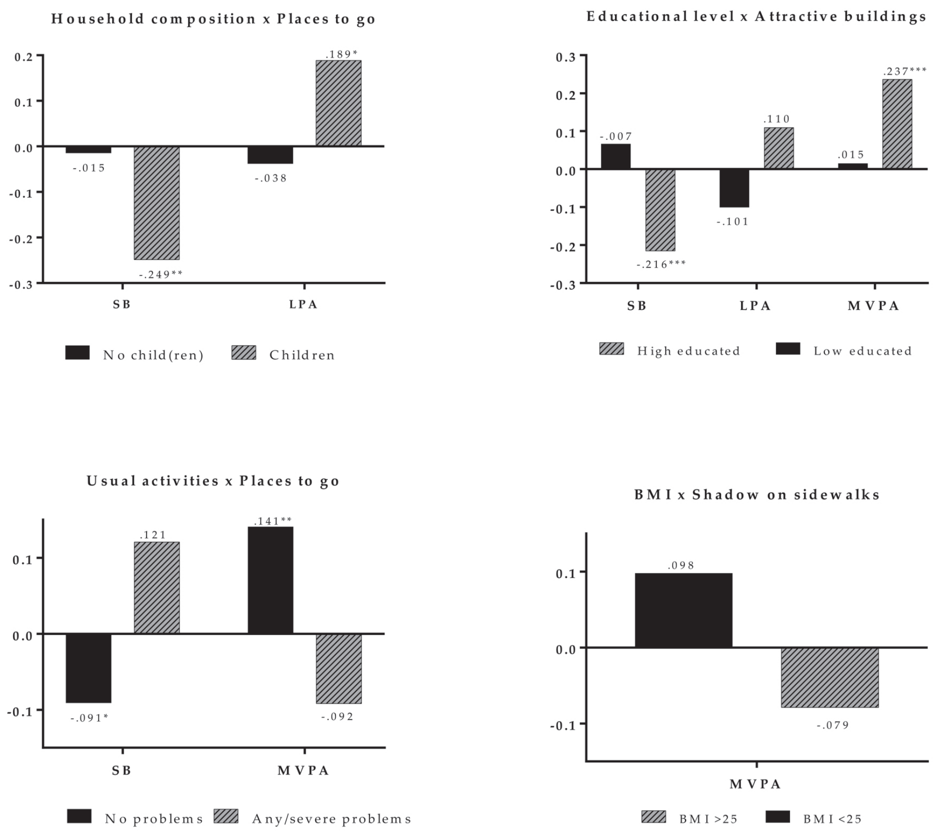

Figure 1. Interactions between personal characteristics (socio-demographic and HRQoL) and PA-facilitating BE characteristics.

For PA-hindering characteristics, we found four significant interactions as well. A better perceived safety at night was associated with more SB and less LPA for households with children (β = 0.164, $p < 0.05$ and β = -0.237, $p < 0.001$ respectively). Fewer perceived physical barriers were significantly associated with more SB and less MVPA for participants with a BMI higher than 25.0 (β = 0.134, $p < 0.05$ and β = -0.129, $p < 0.05$, respectively). For households without children and participants with a BMI lower than 25.0, these associations were not significant. For residents experiencing any/severe problems with usual activities, less perceived traffic was associated with less SB (β = -0.285, $p < 0.05$). For participants experiencing any/severe pain, less perceived high speed traffic was associated more MVPA (β = 0.179, $p < 0.05$). There were no significant associations for participants experiencing no problems. Stratification analyses of significant interactions between personal and PA hindering environmental characteristics are illustrated in Figure 2.

CHAPTER 4

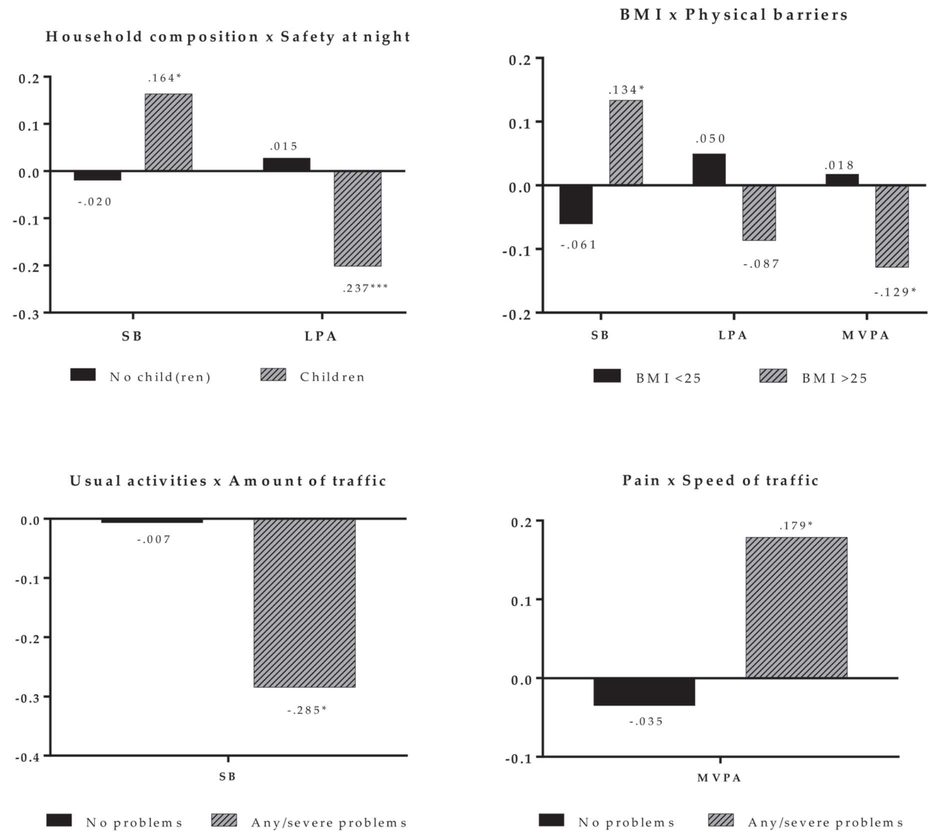

Figure 2. Interactions between personal characteristics (socio-demographic and HRQoL) and PA-hindering BE characteristics.

DISCUSSION

This study explored the associations between socio-demographic characteristics, health-related quality of life (HRQoL), perceived environmental characteristics and PA outcomes. The presence of attractive buildings and the presence of places to go in one's neighborhood were associated with less SB and more MVPA in the total sample. However, our findings suggest that for less advantaged residents in society, it would be more helpful to remove barriers such as heavy traffic rather than introduce PA-facilitating characteristics such as the presence of destinations in the neighborhood and improved aesthetics.

Consistent with other studies, we found that having a higher BMI and experiencing any/severe problems regarding self-care and usual activities were associated with more

SB and less LPA and MVPA [152-154]. Living with children was associated with less SB and more LPA compared to living without children, which was also shown in a recent systematic review [58]. In contrast to the majority of the existing literature, we found that women engaged in less SB and more LPA [133].This exchange between SB and LPA might indicate that women substitute sitting by activities such as cleaning and taking care of children, which are all considered to be light physical activities [155]. We also found that experiencing any/severe pain or discomfort was associated with more MVPA compared to those who did not experience any pain/discomfort. An explanation for this unexpected finding could be that participants with complaints of pain might be engaged in physical therapy, leading to more exercise-related MVPA during the week. A U-shaped association between chronic pain and PA has been suggested [156], in which small amounts and very large amounts of PA are associated with chronic pain.

LPA was only associated with personal characteristics and not with environmental ones. This might be explained by the nature of light physical activities, which are often indoor activities such as household chores or caring for children [155]. These indoor activities are possibly less affected by perceptions of the environment compared to outdoor activities. With respect to environmental characteristics, our study showed that the presence of attractive buildings in the neighborhood was associated with less SB and more MVPA, which is supported by previous literature [138, 157, 158]. Remarkably, another European study found that living in a neighborhood with a higher score for perceived aesthetics was associated with more total self-reported sedentary behavior [159]. These contrasting findings in a fairly comparable sample and context could be due to differences in measuring methods for SB or the difference between neighborhood- and individual-level information on aesthetics.

The presence of places to go within walking distance was associated with more MVPA, which was also supported by previous studies [138, 158]. We unexpectedly found that a higher score for crime, indicating less perceived crime in the neighborhood, was associated with less MVPA, which contradicts the majority of the literature findings [141]. A possible explanation might be that the more active residents are also more aware of the crime in their neighborhood compared to their sedentary counterparts. It could also reflect a lack of alternatives to walking for those living in an area with more crime [160]. It might be helpful to add objective crime rates to investigate this association in more detail [141, 154]. The majority of the NEWS-A variables were not associated with SB, LPA or MVPA, after controlling for personal characteristics (socio-economic demographics and HRQoL). This might be due to the difference in the specificity of the PA measurements and the NEWS-A questionnaire. The NEWS-A assessed the perceived activity-friendliness of the participants' neighborhood, but PA measurements were not restricted to a specific

area. Context-specific PA measurements might help to clarify the relation between perceived neighborhood environment and PA outcomes, based on the actual exposure to the neighborhood environment. The presence of PA-facilitating characteristics such as attractive buildings and places to go within walking distance were associated with less SB and more MVPA in the total sample. However, moderation analyses showed that these associations were only significant for higher educated individuals and individuals without problems regarding usual activities. For the more vulnerable individuals in society, we did not find these significant associations and stratified analyses even showed an opposing trend. Explorative analyses of our data showed that even in some area-level low-SES neighborhoods the higher educated participants scored higher on the presence of attractive buildings, compared to their lower educated counterparts. For the more vulnerable individuals experiencing problems with usual activities and pain, we found that fewer PA-hindering characteristics, such as heavy and speeding traffic, resulted in less SB and more MVPA. There was no significant association for residents without problems. This indicates that traffic is a PA-hindering factor for people who experience problems, while people without problems can overcome these barriers in daily life. This contrasts somewhat with the findings of Carlson et al. (2014), who reported that PA levels of the more advantaged individuals may be impacted more by neighborhood safety compared to the less advantaged individuals [161]. However, Carlson and colleagues used educational level, ethnicity and income for interaction terms, rather than quality of life. Our findings do not support the statement of Mertens et al. (2017), that built environmental interventions could be positive for everyone or at least do not disadvantage subgroups [162]. Indeed, the presence of attractive buildings and the presence of destinations within walking distance can improve PA levels for the total population, but from a socio-economic health inequality perspective, the opposite trend between PA-facilitating characteristics and PA for the less advantaged residents indicates the need for specific research attention. Our results suggest that structural interventions implementing PA-facilitating features could increase socio-economic health inequalities because they may lead to increased PA levels of the more advantaged individuals only. Longitudinal, experimental studies are necessary to confirm these results, and they should be taken into account when designing interventions targeting the reduction of socio-economic health inequalities.

Two interactions showed associations that were difficult to explain. The absence of physical barriers (railroads, rivers, highways), was associated with more SB and less MVPA in overweight residents, while an opposite but non-significant trend was detected for people with a normal weight. For residents in a household with children, more safety at night was associated with more SB and less MVPA, compared to residents in a household without children. The use of context-specific analyses in which the location of PA behavior is included, might be helpful to examine whether there is a logical pattern explaining these unexpected findings, our whether these findings are more likely to be type I errors. The strength of this study is the objective measurement of PA and SB outcomes. In contrast to the majority of the studies, this study included HRQoL as a possible moderator of PA and paid attention

to health inequalities that might be influenced by the environment. An important limitation of this study is its cross-sectional design, which makes it impossible to detect causal relationships. The percentage of non-western residents who participated was too low to control for ethnicity in the models, which affects generalizability of the results. The lack of variation on the NEWS-A item “presence of sidewalks” was very low: 96% (n = 597) of the participants agreed or strongly agreed with the statement that sidewalks were present in their neighborhood. Therefore, we decided to exclude this variable from our analyses. Moreover, the sample was fairly high educated (53%) and retired adults might be overrepresented in the sample. Compared to other studies [42,43], PA levels were generally high. This indicates that the recruitment strategies led to increased self-selection of active adults into the study. We found differences in MVPA levels between VM and VT calculations, though the relative difference between the two methods was comparable with other studies [163, 164]. This emphasizes a limitation of the use of accelerometry in PA research. There are various data-processing protocols and different cut-off values that affect the estimation of the actual energy expenditure. Also, cut-off points are developed in relatively controlled research settings, which might induce inaccuracies when using them in a free-living environment [165]. Lastly, the large number of possible interactions between personal and environmental characteristics that were tested increased the chance of type I errors, i.e., detecting interactions that are not present. To reduce this risk, the suggested significance level for interaction terms of <0.10 [166] was reduced to < 0.05. We found more significant interaction terms than expected based on coincidence.

CONCLUSIONS

More PA-supportive environments such as the presence of places to go within walking distance and the presence of attractive buildings can lead to a decrease in SB and an increase in MVPA, but might not affect LPA. However, the potential of the built environment to affect PA outcomes may differ for advantaged and disadvantaged individuals in society. To design structural built environmental interventions that reduce socio-economic health inequalities, more context-specific research and (natural) experiments are needed. These studies can help to investigate causal relationships between the socio-demographic characteristics, health related quality of life, environmental characteristics and PA outcomes.

CHAPTER 5

Combining Accelerometry and GPS to Assess Neighborhood-Based Physical Activity: Associations With Perceived Neighborhood Walkability

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ABSTRACT

This study explored associations between perceived neighborhood walkability and neighborhood-based physical activity (NB-PA) and assessed possible moderation effects of the amount of time spent in the home neighborhood and individual characteristics (i.e., educational level and health-related problems). In 2016 to 2017, 509 Dutch adults, living in the South Limburg area, were included. Context-specific PA levels were measured using the Actigraph GT3X+ accelerometer and the Qstarz BTQ1000XT GPS-logger. Perceived neighborhood walkability, level of education, work status, and health-related quality of life were measured with validated self-report instruments. Results showed that individuals with a lower level of education or health-related problems spent more time in the home neighborhood. The perceived neighborhood walkability only affected NB-PA for individuals spending a relatively large amount of time in their home neighborhood. PA-facilitating features in the home neighborhood, for example, aesthetics, were only associated with more NB-PA for individuals without health-related problems or with a higher level of education.

INTRODUCTION

Despite the growing attention being paid to physical activity (PA) and its positive effects on health, the levels of physical inactivity of the global population did not significantly change between 2001 and 2016 [9]. In 2016, the prevalence of physical inactivity in high-income Western countries was about 37% [9]. These insufficient PA levels are present throughout the population, though more disadvantaged individuals, with a lower educational level or lower socioeconomic status (SES), are less likely to engage in leisure-time PA compared with the more advantaged people in society [167]. However, socioecological models suggest that PA behavior is not only affected by personal and socioeconomic characteristics, but also by environmental and policy factors [168]. Accordingly, local governments are starting to adopt more upstream, structural interventions to affect the PA levels of the whole population, for example, by designing healthy, active cities and walkable environments [136, 169].

Yet, the literature is still inconclusive about the association between the built environment and PA, partly due to differences in methods, contexts, and individuals' exposure to the physical environment under study [29, 30]. From a socioecological perspective, an individual's behavior is influenced both by the environment and by individual factors [16]. This implies that the same physical environment might have different effects on individuals with different characteristics. SES is one of the most investigated individual factors and is mostly indicated by income, educational level, or occupational status. Goodman et al. (2013) demonstrated that new infrastructures promoting PA might be used more often by residents with a higher educational level or income and by those with a better general health [170]. However, other studies found no interactions between the environment and neighborhood-level SES, so the evidence is still inconclusive [171, 172]. In addition, Alfonzo (2005) proposed the hierarchy of walking needs, arguing that the feasibility of walking, that is, the physical ability, is a fundamental factor in the relationship between environment and walking behavior [142].

These inconsistencies might be due to measurement bias, introduced by differences in the specificity of the measurement methods used [31, 173]. PA measurements can be roughly divided into time-specific and context-specific ones. Time-specific measurements determine the total amount of PA in a certain length of time, regardless of the environment in which it took place. Over the past decades, several device-based (e.g., accelerometers and pedometers) and subjective (e.g., the International Physical Activity Questionnaire [IPAQ]) time-specific PA measurements have been developed [40]. Context-specific PA measurements assess the amount of PA in a specified physical environment. As it is a complex matter to determine which physical environments people are exposed to during the day, most context-specific studies focus on the home neighborhood environment when exploring associations between the physical environment and PA. For example, the recently developed neighborhood-adapted version of the IPAQ (N-IPAQ) subjectively assesses PA levels in the home neighborhood, without explicitly defining what the home neighborhood is [174]. In objective measurements, mostly accelerometers and global positioning systems (GPS) are used to assess the amount of PA at a specific location [42]. In these device-based measurements, the home neighborhood is usually defined as a buffer, for example, radial or street-network buffer, around the home address. It is widely recognized that objective and subjective measurements of PA lead to different and sometimes inconsistent outcomes [43]. Research also suggests that using time-specific or context-specific measurements of PA leads to differences in their association with the built environment [44]. To date, it is not known whether the amount of time that individuals spend in the home neighborhood is affecting this association as well.

The abovementioned inconsistencies in the literature demand further, in-depth exploration of the relationship between the built environment and PA, using individual-level personal characteristics and context-specific PA measurements. Therefore, the first aim of this study was to explore neighborhood-based PA levels and sedentary behavior (SB) and to assess differences between more and less advantaged individuals in society, based on educational level and health-related problems. Subsequently, we assessed the associations between perceived neighborhood walkability and neighborhood-based PA. As we expected the PA behaviors of individuals who spend more time in their home neighborhood to be affected more by the perceived neighborhood walkability, the second aim was to study the effect of the time that was spent in the home neighborhood on the relationship between the perceived neighborhood walkability and neighborhood-based PA. Finally, we explored whether these associations differed for subgroups based on educational level and health-related problems.

METHOD

Study Design and Sample

Data for this cross-sectional study were collected between September 2016 and July 2017 in two cities in the South Limburg region of the Netherlands: Maastricht and Heerlen. The Maastricht University Medical Center (MUMC+) medical ethics committee reviewed the study protocol and concluded that formal ethical approval was not required (METC 16-4-109). All participants received written information and provided signed informed consent. Eligible participants (≥18 years, able to walk without walking aids) were recruited via social media, posters, flyers, advertisements in local and regional newspapers, and personalized mailing, which resulted in a total of 758 included participants. The study materials were

handed out to the participants in their community centers, and after completion of the measurements, the materials were picked up by the researcher at the participants' home.

Accelerometry and GPS Measurements of PA Behavior and Location

To measure context-specific PA, both PA and location data were collected. The participants were instructed to wear an Actigraph GT3X+ activity monitor (Actigraph, Pensacola, FL, USA) and a Qstarz BT-Q1000XT GPS-logger (Qstarz International Company, Taipei, Taiwan) for 7 consecutive days [175]. The devices were worn on an elastic belt on the right hip. In the daytime, the devices were only removed during activities involving water, for example, bathing and swimming. Participants were asked to remove the belt and charge the GPS-logger overnight, using the supplied charger.

Questionnaires

During the week of the device-based measurements, participants completed a questionnaire asking about sociodemographic characteristics, health-related quality of life (HRQoL), and the perceived neighborhood walkability.

Sociodemographic Characteristics

Participants reported their gender (0 = male; 1 = female), age, educational level (recoded into 0 = lower educated; 1 = higher educated, for higher professional education or higher), work status (recoded into 0 = not employed; 1 = employed), height, weight, home address and, if applicable, working address. Body mass index (BMI) was calculated using self-reported height and weight. The dichotomous variable for educational level was used in the subgroup analyses.

Health-related quality of life

The validated EuroQol-5 Dimension (EQ-5D) questionnaire was used to assess the HRQoL in five domains (mobility, daily activities, self-care, pain/ complaints, and mood) and at three levels (no problems, some problems, and severe problems) [148]. For all five domains, a dichotomous variable was created for experiencing no problems (0) or experiencing any/severe problems (1). A problem score was defined as either experiencing no problems in any of the domains (0) or experiencing any/severe problems in one or more domains (1). The dichotomous variable "experiencing health-related problems" was used in the subgroup analyses.

Perceived Neighborhood Walkability

The perceived neighborhood walkability was assessed using the abbreviated version of the Neighborhood Environment Walkability Scale (NEWS-A), which is a validated measure for neighborhood walkability [149, 176]. The following subscales were included in the questionnaire: access to facilities, aesthetics, infrastructure and safety for walking, traffic hazards, crime, lack of parking spaces, hilliness, and physical barriers. All NEWS-A items were scored on a 4-point scale, and if necessary, items were recoded to create scales in which higher scores reflected a more activity-friendly neighborhood environment. Scores ranged from 1 (nonwalkable neighborhood environment) to 4 (very walkable neighborhood environment).

Data Processing

Actigraph raw vertical axis data (30 Hz) were downloaded into Actilife version 6.11.7 (Actigraph) and transformed into activity counts for 10-s epochs. Qtravel software version 1.52.000 (Qstarz International Company) was used to set the GPS-logger to record data at a 10-s epoch and to download the data afterwards. GPS and accelerometer data were merged using the Personal Activity and Location Measurement System (PALMS), which is a validated tool to combine these types of data [177]. In PALMS, vertical axis cut points were used to identify SB (0–99 counts per minute [cpm]), light PA (LPA; 100–1,951 cpm), and moderate-to-vigorous PA (MVPA; >1,951 cpm) [147]. A valid measurement day consisted of at least 8 hr of combined GPS and accelerometer wear time, and a valid week consisted of at least 5 valid days, which could include weekends [178]. Home and work addresses were geocoded using ArcMap version 10.6.1 (Environmental Systems Research Institute, Redlands, CA, USA). Street network buffers of 1.0 km around home and work addresses were created for each participant [179]. These buffers defined the personal home and work neighborhoods. Individual-level street network buffers and the merged PA and location data were combined in a PostgreSQL databases (PostgreSQL Global Development Group, Berkeley, CA, USA) to analyze when and for how long participants engaged in SB, LPA, and MVPA in the prespecified home and work buffers, and to calculate outcome measures of context-specific PA levels.

Statistical Analyses

All statistical analyses were conducted using SPSS version 23.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were used to describe sample characteristics, mean values, and standard deviations of sociodemographic characteristics, HRQoL, perceived neighborhood walkability, PA levels, and SB. Independent sample t-tests were used to assess if context-specific PA levels differed between subgroups. Associations between personal characteristics, perceived neighborhood walkability, and PA outcomes were assessed using multivariate linear regression analyses. To assess the main effects of environmental characteristics on PA, we used a hierarchal regression method with two blocks. The first block contained sociodemographic characteristics, and the second block contained the subscales of the NEWS-A. The backward deletion method was used for each block to exclude the least significant variables until all remaining

variables were statistically significant ($p < .05$). The final model, containing both blocks, is presented in the "Results" section. Interactions between the time exposed to the home neighborhood environment and perceived neighborhood walkability were calculated and added to the model, to test a possible moderation of the amount of exposure on the associations between the perceived neighborhood walkability and neighborhood-based MVPA. Stratified analyses were performed in case of significant interactions ($p < .10$; Stone-Romero & Liakhovitski, 2002 [166]). Finally, interactions between the perceived neighborhood walkability and individual characteristics (i.e., educational level and health status) were added to the model, to explore possible interactions between the perceived neighborhood walkability and individual factors. In case of significant interactions ($p < .10$), additional sensitivity analyses were conducted with stratification by educational level and health status.

RESULTS

Participant Characteristics

Of the 758 participants who were included in this study, 37 (5%) did not provide valid questionnaire data. Another 212 (28%) participants failed to provide at least 5 valid days of PA and location data, leaving 509 participants in the final sample. Table 1 presents the participant characteristics, HRQoL, and the perceived neighborhood walkability of the total sample and the subgroups based on educational level and health-related problems. Of the total sample, about half was male, and half of the sample had a higher level of education. About 46% of the participants was not employed, which included unemployed and retired persons and individuals declared unfit to work. The mean BMI was 25.1 kg/m2.

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The sociodemographic characteristics, HRQoL, and the perceived neighborhood walkability are presented in Table 1 both for the whole sample and for the subgroups. Of the total sample, hardly any of the participants experienced problems regarding self-care. About 10% to 11% experienced problems regarding mobility, daily activities and/or mood, while almost a third of the study sample experienced pain/complaints. Overall, about 63% of the participants did not experience any problems in any domain. The lowest score for neighborhood walkability (NEWS-A) was found for the subscale lack of parking spaces ($M = 2.1$, $SD = 0.8$). The subscales hilliness and physical barriers had the highest mean score ($M = 3.5$, $SD = 0.6$; $M = 3.5$, $SD = 0.7$, respectively).

Table 1. Socio-demographic characteristics, health-related quality of life and NEWS-A scores of the total study sample.

Socio-demographic characteristics	%/Mean (SD)
Gender (% male)	47.2
Age (y)	57.1 (15.5)
Educational level† (% higher educated)	53.2
Work status (% Employed)	53.6
Body Mass Index (kg/m²)	25.1 (4.3)
Health-related quality of life	**%**
Mobility (% any/severe problems)	11.4
Daily activities (% any/severe problems)	10.6
Self-care (% any/severe problems)	1.2
Pain/complaints (% any/severe problems)	31.3
Mood (% any/severe problems)	11.0
No problems in any domain	64.1
NEWS-A scores	**Mean (SD)**
Access to facilities	3.4 (0.5)
Infrastructure and safety for walking	2.8 (0.3)
Aesthetics	2.7 (0.6)
Traffic Hazards	2.8 (0.5)
Crime	3.1 (0.4)
Lack of parking	2.1 (0.8)
Hilliness	3.5 (0.6)
Physical barriers	3.5 (0.7)

†= 5 participants reported a non-categorizable educational level

Overall and Context-Specific PA Levels

Table 2 shows the overall and context-specific PA levels of the total sample as well as of subgroups within the sample. The average wear time of the total sample was 14.2 hr per day, of which 64.2% was spent in SB, 31.4% in LPA, and 4.2% in MVPA. More than half of the total wearing time was spent at home or in the home neighborhood. When present at home or in the home neighborhood, most of the time was spent in SB.

PA levels based on educational level

The average wear time per day did not differ between lower educated and higher educated individuals, but lower educated individuals spent significantly more time at home and in their home neighborhood. Overall, higher educated adults spent significantly more time in SB compared with lower educated individuals, while lower educated individuals spent relatively more time in LPA. Sensitivity analyses showed that the differences in total SB and LPA were due to differences in PA levels at work and the work neighborhood (supplementary Table S1). Whenever they were present in the home neighborhood, the relative time spent in SB, LPA, and MVPA was similar for lower educated and higher educated adults.

PA levels based on health-related problems.

The average wear time was similar for individuals with and without health problems. Overall, the two groups spent the same relative amount of time in SB and LPA, but individuals without health-related problems spent significantly more time in total MVPA. Individuals with health-related problems spent a greater share of the total time at their home and in their home neighborhood compared with individuals without health-related problems. The relative amount of time spent in SB, LPA, and MVPA whenever present in the home neighborhood did not differ between the two groups. Because MVPA levels at work and in the work neighborhood did not explain the differences in total MVPA levels between individuals with and without health-related problems (supplemental Table S1), we focused our subsequent analyses on the associations between the perceived neighborhood walkability and neighborhood-based MVPA.

Table 2. Total and context-specific physical activity levels for the total sample and subgroups based on educational level and health-related problems.

	Total sample (N=509)	Educational level†				Health-related problems			
		Lower educated (N=236)	Higher educated (N=268)	Effect size *d*	*p*	No problems (N=326)	Any/severe problems (N=183)	Effect size *d*	*p*
Total physical activity									
Wear time in hour (SD)	14.2 (1.3)	14.1 (1.2)	14.3 (1.3)	0.16	.142	14.3 (1.2)	14.1 (1.4)	0.15	.352
% SB (SD)	64.2 (8.8)	62.7 (8.8)	65.5 (8.6)	0.32	**.000**	64.4 (8.2)	63.9 (9.7)	0.06	.544
% LPA (SD)	31.4 (8.2)	33.1 (8.5)	29.8 (7.6)	0.41	**.000**	31.1 (8.0)	31.8 (8.5)	0.08	.363
% MVPA (SD)	4.2 (3.0)	4.2 (3.0)	4.3 (3.0)	0.03	.600	4.5 (2.9)	3.8 (3.1)	0.23	**.007**
Context-specific physical activity									
At home									
Presence (% Wear time/day) (SD) – hr (SD)	49.6 (19.5) – 7.1 (2.9)	51.7 (18.4) – 7.3 (2.6)	47.7 (20.3) – 6.9 (3.1)	0.56	**.021**	47.1 (18.5) – 6.7 (2.7)	54.2 (20.3) – 7.7 (3.1)	0.37	**.000**
% SB (SD)	64.2 (8.8)	65.3 (9.7)	65.5 (8.6)	0.02	.991	65.0 (9.5)	65.8 (10.3)	0.06	.377
% LPA (SD)	33.5 (9.1)	33.7 (9.4)	33.3 (9.0)	0.04	.582	33.9 (9.0)	32.7 (9.2)	0.13	.139
% MVPA (SD)	1.0 (1.2)	1.0 (1.0)	1.1 (1.3)	0.08	.405	1.1 (1.2)	1.0 (1.2)	0.08	.346
At home + home neighborhood									
Presence (% Wear time/day) (SD) – hr (SD)	58.3 (19.2) – 8.3 (2.9)	61.5 (18.2) – 8.7 (2.6)	55.6 (19.7) – 8.0 (3.0)	0.58	**.001**	55.4 (18.4) – 7.9 (2.8)	63.7 (19.3) – 9.0 (2.9)	0.44	**.000**
% SB (SD)	63.7 (9.5)	63.8 (9.3)	63.5 (9.7)	0.03	.733	63.5 (9.0)	64.0 (10.3)	0.05	.507
% LPA (SD)	33.0 (8.6)	33.3 (8.9)	32.8 (8.4)	0.06	.484	33.3 (8.3)	32.7 (9.0)	0.07	.416
% MVPA (SD)	3.1 (3.0)	2.8 (2.5)	3.3 (3.3)	0.17	.078	3.2 (3.0)	2.8 (2.9)	0.14	.078

†= 5 participants excluded based on non-categorizable educational level; SD= Standard deviation; SB= Sedentary behavior; LPA= light physical activity; MVPA= moderate-to-vigorous physical activity

Associations between perceived neighborhood walkability and neighborhood-based PA

In the total sample, being younger was associated with more MVPA in the home neighborhood (Table 3).

Table 3. Associations between personal and environmental characteristics, and MVPA in the home neighborhood, for individuals spending more or less time in their home environment.

	Total sample (N=509)	Less time than median in neighborhood (N=255)	More time than median in Neighborhood (N=254)
	β	β	β
Personal characteristics			
Age	-.222**	-.189**	-.232**
Gender			-.183**
BMI			-.135*
Educational level			-.138*
Explained variance (R^2)	*.052*	*.037*	*.074*
Environmental characteristics			
Access to facilities	.099*		-.138*
Lack of parking	.099*	.135*	
Explained variance (R^2)	*.071*	*.055*	*.108*

* = P<.05; **=P<.01

When controlling for age, a better perceived access to facilities and an increased perception of a lack of parking spaces were associated with more MVPA. A significant interaction was found for time of exposure to the home neighborhood and perceived neighborhood walkability (Aesthetics × Exposure; $t = 1.972$, $\beta = .085$, $p = .049$). We stratified for the median amount of exposure to the home neighborhood (median = 505 min/day). For individuals spending more time in the home neighborhood, there was a negative association between age, gender (men), BMI, and educational level with more neighborhood-based MVPA. For individuals spending less time in their home neighborhood, only age was associated with neighborhood-based MVPA. The lack of parking spaces was associated with more MVPA, but only for individuals who spent less time in their neighborhood. Access to facilities was positively associated with more MVPA, but only for individuals spending more time in their home neighborhood. The explained variance of the final model was 5.3% higher for individuals spending more time in their home neighborhood, compared with individuals spending less time in their home neighborhood.

Table 4. Associations between personal and environmental characteristics and neighborhood-based MVPA, stratified for educational level and time spent in neighborhood.

	Less than median time spent in neighborhood				More than median time spent in neighborhood			
	Educational level†		Health-related problems		Educational level		Health-related problems	
	Lower educated (N=105)	Higher educated (N=146)	Any/ severe problems (N=70)	No problems (N=183)	Lower educated (N=131)	Higher educated (N=122)	Any/severe problems (N=113)	No problems (N=143)
	β	β	β	β	β	β	β	β
Personal characteristics								
Age		-.251**		-.192**	-.237**	-.178*		-.196*
Gender					-.279**			
BMI						-.204*	-.207*	
Educational level			.270*					
Explained variance (R^2)	-	.063	.073	.037	.096	.098	.043	.041
Environmental characteristics								
Access to facilities						.198*		.206*
Aesthetics						.233**		
Physical barriers						-.182*		
Traffic							-.240*	
Explained variance (R^2)	-	-	-	-	-	.209	.084	.083

†= 5 participants excluded based on non-categorizable educational level; * = P<.05; **=P<.01

Interactions between perceived neighborhood walkability, health status, and educational level were tested for individuals spending more and less time in their home neighborhood. Significant interactions were found for these personal characteristics, but only in individuals spending more time in their home neighborhood (Health status × Access to facilities, t = −1.731, β = −.110, p = .085; Educational level × Aesthetics, t = 2.458, β = .148, p = .015). Stratified analyses were performed to explore these interactions further (Table 4). For individuals spending less time than median in their home neighborhood, none of the environmental characteristics was associated with neighborhood-based MVPA. For the lower educated individuals who spent little time in their home neighborhood, no significant associations were found at all. The explained variance of the final models ranged between 0% and 7.3%.

For individuals spending more time than median in their home neighborhood, differences were found in the final models for lower educated and higher educated individuals and for individuals with and without health problems. None of the environmental characteristics were associated with neighborhood-based MVPA in lower educated individuals. For higher educated individuals, access to facilities, and aesthetics were positively associated with MVPA. Fewer physical barriers were associated with less MVPA. Neighborhood-based MVPA levels were negatively associated with less traffic for individuals spending more time in their neighborhood and experiencing any/severe health-related problems. For individuals without health-related problems, a higher score on aesthetics was associated with more neighborhood-based MVPA. The explained variance of the models for individuals spending more time in their home neighborhood ranged between 8.3% and 20.9%.

DISCUSSION

The aims of this study were to explore context-specific PA behavior in more and less advantaged individuals in society, to assess the associations between the perceived neighborhood walkability and neighborhood-based PA, and to determine the effect of the time spent in the home neighborhood and individual characteristics on this association.

We observed differences in the total amount of PA per day and context-specific behaviors between subgroups based on educational level and health status. Regarding the total PA per day, lower educated individuals spent less time in SB and more time in LPA. Sub analyses showed that this was mainly explained by the differences in PA and SB levels at work and in the work neighborhood. These differences between higher educated “white-collar” employees, with highly sedentary jobs, and lower educated “blue-collar” employees were also found in other European studies [172, 180, 181]. We also found lower levels of total MVPA in people experiencing any/severe health-related problems compared with people without health-related problems, which is also in correspondence with the existing literature about the relationship between HRQoL and PA [152]. Also, individuals with a lower educational level and/or experiencing health-related problems spent significantly more time in their home neighborhood, which creates an opportunity to increase PA levels by improving the PA friendliness of the home neighborhood. Associations between the perceived neighborhood walkability and neighborhood-based MVPA differed for subgroups. The identified associations between the accessibility of facilities, lack of parking spaces, and neighborhood-based MVPA in the overall sample supported the results of previous studies [182]. However, the presence of PA-facilitating characteristics was only associated with MVPA for higher educated individuals, or individuals without health-related problems. On the contrary, the absence of PA-hindering factors, such as the lack of parking spaces, was only associated with more MVPA for the less advantaged. Both findings are in line with a previous study [30]. In light of the hierarchy of walking needs, it might be that for the less advantaged subgroups the lower order needs, that is, feasibility, accessibility and safety, have not been fulfilled, while for the more advantaged subgroups these needs were fulfilled and the higher order needs, that is, comfort and pleasurability, became more important [142].

Besides socioeconomic factors, the amount of time that was spent in the home neighborhood also affects the relationship between the environment and PA. Notably, we identified no associations between the perceived neighborhood walkability and neighborhood-based MVPA for individuals spending relatively little time in the home neighborhood. The explained variances in these models were low (0%–7%), in line with findings by De Bourdeaudhuij and colleagues (2003) [151]. For individuals spending relatively more time in the home neighborhood, the explained variance of the final model increased up to 20.9%. This implies that the perceptions of the physical environment have more effect on PA levels for individuals spending more time in their home neighborhood, which are often the more disadvantaged people in society. We identified some unexpected negative associations. In contrast to, for example, Foraster et al. (2016) and Jongeneel-Grimen et al. (2013), less perceived traffic was associated with less MVPA in our current study [183, 184]. This might be due to the fact that people who are more physically active in their neighborhood are more aware of the traffic. Similarly, fewer perceived physical barriers were associated with less MVPA. This could be due to the increased directness of routes without physical barriers such as highways and rivers, leading to shorter trips. However, longitudinal data are necessary to explore these unexpected associations further.

To our knowledge, this is the first study that takes into account the actual time spent in the home neighborhood when assessing the relationship between the perceived neighborhood walkability and PA. Previous experimental studies reported that people living closer to an intervention in the built environment are more affected by it compared with people living further away [65, 66, 77]. This study adds that it is necessary to measure the actual exposure to the environment of interest because the physical environment might only affect individuals who spend more time in that specific environment.

Although several studies identified associations between the physical environment and PA, only a few identified differences between subgroups in society [28, 159, 172, 185]. This might be due to the mismatch of the level (i.e., individual or neighborhood level) or context specificity of measurements. PA behaviors are typically measured at the individual level, while objective neighborhood environment or neighborhood walkability is often measured at the neighborhood level using administrative neighborhood boundaries [47, 172, 185]. Some of these studies also used neighborhood-level characteristics to stratify subgroups in their sample [47, 172], while it is not known whether these characteristics are applicable for all participants of the particular neighborhood. The use of individual data on all levels, that is, PA, environmental characteristics, and sociodemographic characteristics, might be helpful in future research clarifying possible differences between subgroups in society. The strength of this study is the objective and context-specific measurement of PA and the incorporation of the time that individuals were actually present in their home neighborhood. This study is one of the first that explored subgroups based on health status, which seems to impact the associations between the environment and PA. Furthermore, we reached a high compliance with the wear protocol, with only a few participants excluded and a mean wear time of 14.2 hr a day. One limitation of this study is its cross-sectional design. It was not possible to detect causal relationships using this research design. Another limitation is the age distribution in the study sample. As the mean age of the participants was 57.1 years, a substantial proportion of them was retired. Thus, the amount of time spent in the home neighborhood was possibly higher in the study sample compared with the total population. This implies that the generalizability of the results might be better for a slightly older population than for the general population of adults. Finally, it should be noted that our results concern associations between the perceived neighborhood walkability and PA. Research suggests a limited correlation between the perceived environment and the objectively measured environment, for example, measured by geographical information systems [186], which implies that a change in the environment might not directly evoke a change in the perceptions of the environment.

CONCLUSION

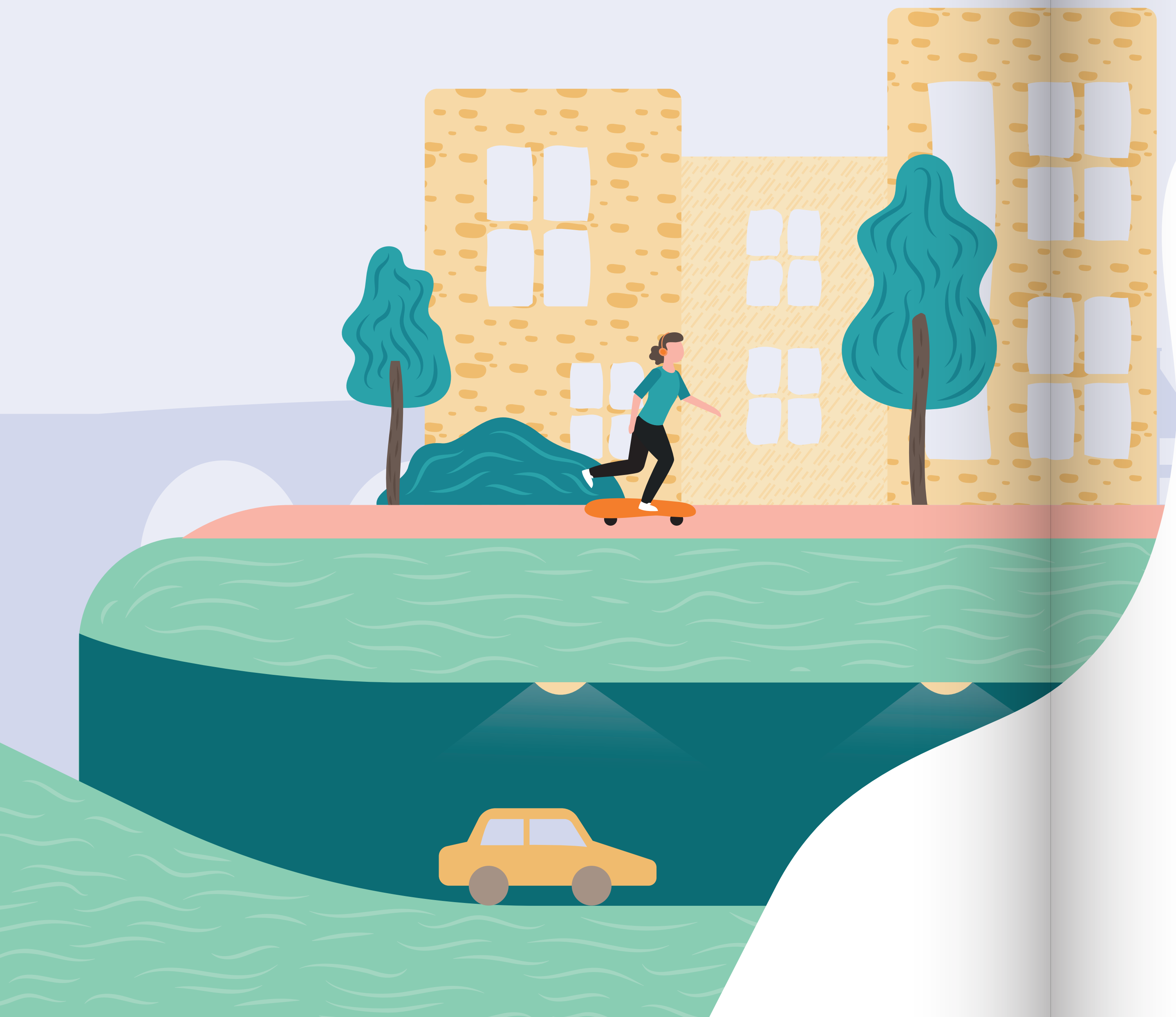
Individuals with a lower educational level or with health-related problems spend more of their time in their home neighborhood, which creates opportunities to increase PA levels by improving the quality of that neighborhood. For those individuals, however, facilitating features in the physical environment, for example, appealing aesthetics and access to facilities, might not have the same positive effect they would have on individuals without problems or a higher education. The results of this study suggest that the neighborhood environment might only affect individuals who spend relatively much time in their neighborhood. We recommend that researchers and city planners take into account the subgroup differences in associations between the perceived neighborhood walkability and PA when designing PA-promoting environments. From a health-equity perspective, city planners should consider whether their plans affect lower SES populations with at least as much impact as they affect higher socioeconomic groups. Our results underline the relevance of this consideration, because the variance in MVPA levels in lower educated participants could not be explained by perceived neighborhood walkability. Longitudinal experiments, controlling for exposure, are necessary to confirm the identified associations and subgroup differences.

APPENDIX

Supplementary material

Table S1. Total and context-specific physical activity levels at work and in the work neighborhood.

	Total sample	Lower educated (N=87)	Higher Educated (N=136)	Effect size *d*	*p*	No problems (N=168)	Any/severe problems (N=57)	Effect size *d*	*p*
At work	N=225	N=87	N=136			N=168	N=57		
Wear time %/day (SD) – hr (SD)	6.7 (14.9) – 1.0 (2.1)	5.3 (12.8) – 0.8 (1.9)	8.0 (16.4) – 1.1 (2.3)	0.18	**.042**	7.4 (15.0) – 1.5 (3.8)	5.6 (14.8) – 1.2 (3.6)	0.12	.206
% SB (SD)	59.6 (22.2)	50.8 (23.3)	65.5 (19.6)	0.18	**.000**	60.7 (21.7)	56.4 (23.9)	0.19	.216
% LPA (SD)	35.3 (20.5)	44.9 (22.3)	29.1 (16.8)	0.80	**.000**	34.0 (19.7)	39.6 (22.5)	0.26	.074
%MVPA (SD)	5.1 (8.3)	4.4 (7.0)	5.4 (8.9)	0.12	.356	5.4 (8.9)	4.0 (6.1)	0.18	.272
At work + work neighborhood	N=245	N=99	N=144			N=179	N=66		
Wear time %/day (SD) – hr (SD)	12.8 (20.5) – 1.8 (3.0)	10.5 (19.1) – 1.5 (2.8)	14.8 (21.6) – 2.1 (3.1)	0.21	**.019**	14.2 (20.8) – 2.0 (3.0)	10.2 (20.0) – 1.4 (2.9)	0.18	**.034**
% SB (SD)	59.0 (19.7)	50.4 (21.6)	65.2 (15.5)	0.79	**.000**	60.5 (18.9)	54.8 (21.1)	0.28	**.047**
% LPA (SD)	34.7 (18.2)	43.6 (20.2)	28.3 (13.4)	0.89	**.000**	33.2 (17.2)	39.2 (20.3)	0.32	**.021**
%MVPA (SD)	6.2 (9.8)	5.9 (11.2)	6.5 (8.8)	0.06	.672	6.4 (8.5)	6.0 (12.7)	0.04	.777



CHAPTER 6

Tunneling a crosstown highway: a natural experiment testing the longitudinal effect on physical activity and active transport

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ABSTRACT

In the city of Maastricht in the Netherlands, a highway crossing several deprived neighborhoods was tunneled in 2016. The vacant space on top of this tunnel was redesigned and prioritized for pedestrians and cyclists. The aim of this study was to evaluate the effect of this major infrastructural change, named the Green Carpet, on total and transport-based physical activity (PA) levels. Participants (≥18 years) were part of one of three area-based exposure groups. The maximal exposure group lived in neighborhoods directly bordering the Green Carpet. The minimal exposure group consisted of individuals living at the other side of the city, and the no exposure group consisted of individuals living in a nearby city. Actual use of the new infrastructure was incorporated as a second measure of exposure. Data were collected before and 3-15 months after the opening of the Green Carpet. Device-based measurements were conducted to obtain PA levels and collect location data. Changes in PA over time and intervention effects were determined using linear mixed models. PA levels in the Green Carpet area increased for the maximal and minimal exposure groups, but did not lead to an increase in total or transport-based PA. For the no exposure group, transport-based MVPA decreased and transport-based SB increased. The significant interaction (time x exposure) for transport-based SB, indicated differences in trends between the no exposure and maximal exposure group (B=-3.59, 95% CI - 7.15; -0.02) and minimal exposure group (B= -4.02, 95% CI -7.85, -0.19). Trends in the results based on analyses focusing on actual use and non-use of the new infrastructure were similar to those of the area-based analyses. Results suggest that the Green Carpet led to more PA in this specific area, but did not increase the total volume of PA. The area-based differences might reflect the differences between users and non-users, but we should be careful when interpreting these results, due to possible interference of selective mobility bias. This paper reflects that the relationship between infrastructure and PA is not unambiguous.

BACKGROUND

The detrimental effects of physical inactivity on noncommunicable diseases have been widely studied and the results highlight the need to increase population-wide physical activity (PA) levels in order to improve public health and decrease healthcare costs [4, 7]. According to socioecological models, PA behavior is affected by personal, socioeconomic, environmental, and policy factors [16]. Thus, to increase population-wide PA levels, national and local governments should focus on more structural changes at the environmental, policy, and societal levels [49]. In recent years, several largescale, multi-city studies investigated the potential of the built environment to affect population-wide PA levels [28, 187, 188].

Based on recent systematic reviews, it can be concluded that changes in the built- and natural environments can lead to changes in PA levels of adults, and especially to changes in active transport (AT), i.e. walking and cycling for transport [15, 29, 30, 189]. Moreover, AT might result in additional health benefits over vehicle-based transport, such as the reduction of the emission of, and exposure to, air pollution, and the improvement of neighborhoods' livability by lowering the amount of motorized traffic [190, 191]. Although existing systematic reviews identified relationships between the environment and some types of physical activity behavior, the evidence remains inconclusive. One of the main issues is that the available evidence differs in measuring methods, quality and contexts. More longitudinal, context-specific research is needed to unravel the mechanisms that play a role in the relationship between the environment and behavior [31].

From previous research, we know that exposure to a new or redesigned infrastructure might increase the chance of engaging in AT [68]. However, exposure can be defined in various ways. Measures of exposure might be area-based, mostly consisting of administrative spatial boundaries, whereby exposure is treated as living in a specific area [90]. As exposure might vary within geographical areas, some studies use proximity (e.g. length or travel duration) as a continuous or ordinal measure of exposure [65, 80]. However, this approach assumes that the proximity of the home location to a specific environment is central to classify exposure to this environment [90]. Over the past decade, GPS-based approaches have increasingly been used to assess the actual exposure to a certain area, by combining GPS and geographical information systems (GIS). Following this trend, an increasing number of studies combine device-based location measurements with device-based PA measurements [192, 193]. This type of measurements prevents inconsistencies that typically occur when using self-reported PA measurements, such as inaccurate reporting and reporting bias [194]. However, large-scale evaluations exploring the effects of major infrastructural changes on the PA behavior of adults using both GPS and accelerometry are lacking.

In the city of Maastricht in the Netherlands, a highway crossing several deprived neighborhoods was tunneled in 2016 and the vacant space on top of this tunnel was prioritized for pedestrians and cyclists. The tunneling of this highway has led to a noise reduction of between 5 and 20 dB (depending on the exact location) and a decrease in the amount of nitrogen and particulate matter in the area [195]. Besides air quality, the tunneling also provided the opportunity to evaluate the effect on PA behavior. The aim of this study was to evaluate the effect of tunneling a highway on the overall PA and transport-based PA of people living in the vicinity of this major infrastructurally changed area, called The Green Carpet, compared to individuals living further away within the same city, and individuals living in another city in the same region. A second aim of this study was to explore the differences in PA for individuals that actually used or did not use the Green Carpet. This is the first largescale evaluation to use individual-level device-based measurements of both PA and location in adults.

METHODS

The project: Green Carpet

Since its opening in 1959, the highway A2 crosses residential areas in the east of the city of Maastricht. Due to the enormous increase in traffic over time, the burden on the residents of these areas also increased over time. Therefore, a double-layered tunnel was built to facilitate the traffic passing through the city (www.mijngroeneloper.nl/het-plan/informationenglish). To accommodate the remaining local traffic in the areas on top of the tunnel, two one-way streets were constructed. These one-way streets were separated by a semi-paved middle section, prioritized for use by pedestrians, cyclists and for recreation. This middle section was separated from the adjacent streets by wide strips of grass and trees, creating the so-called 'Green Carpet'. The Green Carpet has a length of 2.3 kilometers. The semi-paved middle section has a width of about 6 meters, while the entire profile of the middle section, the strips with greenery and adjacent one-way streets is about 30 meters in width The Green Carpet was officially opened in spring 2018, but constructions of houses and facilities will continue up until 2026. Images of the intervention area before and after the opening of the Green Carpet can be found in the supplementary material (Figure S1 and S2). Details about the origin and context of the Green Carpet project have been described elsewhere [196].

Study design and participants

This study used data from a non-randomized natural experiment. Natural experiments are alternatives to RCTs in cases in which it is practically or ethically impossible to manipulate exposure to an intervention, such as major changes in infrastructure [39]. The participants of this study were adult (≥18 years) inhabitants of Maastricht and Heerlen, two cities in the South-Limburg region of the Netherlands, which have about 120,000 and 100,000 inhabitants, respectively. Individuals who were not able to walk without walking aids or were not able to fill out a Dutch questionnaire were excluded from participation. Eligible participants were recruited via social media, posters, flyers at supermarkets and local events, advertisements in local and regional newspapers, and via personalized mailings to a random sample of the inhabitants. Baseline measurements of the experiment were performed before the opening of the Green Carpet, between September 2016 and June 2017. The follow-up measurement was conducted between September 2018 and June 2019. Participants were measured in approximately the same week of the year at baseline and during the 2-year follow-up. On average, the time between the opening of the Green Carpet and the follow-up measurement of the individuals in Maastricht was 9.8 months (median: 10.5 months, range: 3-15 months). The Maastricht University Medical Center (MUMC+) medical ethics committee reviewed the study protocol and concluded that formal ethical approval was not required (METC 16-4-109). All participants provided written informed consent. The study is registered at the Netherlands Trial Register (NL8108).

Procedures

PA levels and location data were collected using devicebased measurements, by the Actigraph GT3X+ activity monitor (Actigraph, Pensacola, FL, USA) and the Qstarz BT-Q1000XT GPS logger (Qstarz International Company, Taipei, Taiwan). Participants were instructed to wear both devices on an elastic belt on the right hip, for seven consecutive days at daytime only. Devices were removed during activities involving water, i.e. swimming and showering, and overnight, when the participant charged the GPS logger. Raw accelerometry data (30 Hz) of the vertical axis were downloaded into Actilife version 6.11.7 (Actigraph, Pensacola, FL, USA) and converted to activity counts for 60-second epochs. GPS data were downloaded using Qtravel software version 1.52.000 (Qstarz International Company, Taipei, Taiwan) in epochs of 10 seconds. Accelerometry and GPS data were merged into 60- second epochs using the Human Activity Behavior Identification Tool and data Unification System (HABITUS), which is an updated version of the Personal Activity and Location Measurement System (PALMS) [177]. The GPS and accelerometry data were processed and filtered in HABITUS. Freedson's cut points (1998) were applied to distinguish sedentary behavior (SB; 100 activity counts per minute) from moderate-to-vigorous physical activity (MVPA; >1952 counts per minute) [147]. Invalid GPS data points were identified based on extreme changes in speed (>130 km/hour) and elevation (1000m) between two epochs. Data points were distinguished as 'stationary' points, and points that were recorded during a trip. Activity was classified as a trip if the distance traveled was at least 100 meters and the duration exceeded 120 seconds. A stop of at least 120 seconds at one location was marked as a pause point and a pause of more than 180 seconds was marked as the endpoint of a trip. Periods of at least 60 minutes of zeros were classified as non-wear time and excluded from the analyses. The transport classification algorithm had a minute-level sensitivity of 88.5%, a specificity of 93.4%, and a positive predictive value of 74.9% [177]. The device-based measurements were considered valid if there were at least four days, regardless of week or weekend days, with a minimal wear time of 8 hours per day [178]. The HABITUS output was entered into a purposebuilt PostgreSQL geodatabase which was used to assign datapoints to pre-defined contexts or domains. In this process, datapoints were hierarchically assigned and categorized as being in the home domain, the work domain, on the Green Carpet (Fig. 1) or in the transport domain. Outcomes in this study are the percentage of SB, LPA and MVPA of the total wear time, the percentage of transport-based SB, LPA and MVPA and the percentage of SB, LPA and MPVA at the Green Carpet.

Figure 1. Area-based exposure groups and Green Carpet Area. Left: no exposure (white), minimal exposure (light green) and maximal exposure (dark green) areas in Maastricht and Heerlen. Right: 2.3 km Green Carpet on top of the A2 highway tunnel. Map: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

Measures of exposure

Participants belonged to one of the area-based exposure groups, based on the distance of their residential area to the Green Carpet area. The 'maximal exposure' group consisted of individuals that lived in the neighborhoods directly bordering the Green Carpet, situated at the East side of the city center (Fig. 1; Dark green; East Maastricht, South-East Maastricht). The expected exposure to the Green Carpet, was largest in this group. The 'minimal exposure' group consisted of inhabitants of Maastricht who lived on the western side of the river Meuse and outside the city center (Fig. 1; light green). Participants from these neighborhoods (West Maastricht, North-West Maastricht, South-West Maastricht), might visit the Green Carpet area, but are less likely to be exposed to this area. Individuals living in the 'no exposure' area were inhabitants of the city of Heerlen. Participants of this group were not expected to be exposed to the Green Carpet because they lived approximately 25 kilometers away from the Green Carpet. Heerlen was selected as

comparison area because the selected neighborhoods in this city are comparable to Maastricht with regard to the number of inhabitants, urbanization and the geographical and cultural context. Secondly, for all participants, the actual use of the Green Carpet area was determined using GPS data, whereby, for the participants of all three area-based groups, the use was defined and dichotomized to 0 (did not use Green Carpet area) and 1 (used Green Carpet area) at follow-up.

Covariates

A questionnaire was distributed at baseline and follow-up to assess sociodemographic characteristics, including gender (0= male, 1= female), age, educational level (recoded into 0= lower educated, 1 = higher educated, for individuals with higher professional education or higher), work status (recoded into 0= not working, 1= working) and car ownership (recoded into 0= no car available in household, 1= one or more cars available in household). Also, health-related quality of life was assessed using the EQ-5D-3L questionnaire [148]. For each of the five domains of this questionnaire (mobility, self-care, daily activities, pain and mood) we created a dummy variable for individuals experiencing no problems (0) or any/severe problems (1) in a specific domain. All study materials were distributed from local community centers, and after the 7-day data collection period ended, a member of the research team visited the participants at home to collect the materials.

Statistical analyses

Descriptive statistics were used to describe and compare the baseline characteristics of the participants in the three groups of the experiment. To explore possible baseline differences and conduct dropout analyses, we performed T-tests and Chi-square tests on all covariates. Normality was assumed based on the skewness and the kurtosis of the outcome measures. As mixed models are able to handle missing data in a longitudinal dataset when the covariates are present, changes in outcomes over time and intervention effects were determined using linear mixed models. Also, linear mixed models have the option to account for repeated measures within the individual. For each outcome, we first explored for each group the within-group changes by using time as a fixed factor in the model, while only accounting for repeated measures within persons. Next, an unadjusted model was created by adding an exposure group variable, accompanied by the interaction term between time x area-based exposure group. Lastly, a fully adjusted model was tested using the unadjusted model, supplemented with the covariates described above: age, gender, educational level, work status, car-ownership, and scores on EQ-5D. Sensitivity tests were conducted to validate the results with data of individuals that provided complete cases at both baseline and follow-up. Additionally, we further explored the differences in PA behavior between individuals that actually used the new infrastructure and individuals that did not, defined based on their GPS data. In these analyses, only

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individuals with valid data on both measurement moments were included. All statistical analyses were performed in SPSS version 24.0.0.2 (IBM Corp., Armonk, NY, USA) using a p-value of 0.05 as threshold for significance in all tests.

RESULTS

At baseline, 757 participants were recruited, of which 642 provided valid data at T0 and 362 provided valid data at both T0 and T1. Participants' characteristics

Participants' characteristics

At baseline, participants were on average 56.3 years old. The minimal exposure group was significantly older compared to the no exposure group (Table 1). About half of the sample were male and about half of the sample higher educated. Also, 54.8% of the participants were in employment, while the other 45.2% were retired or unemployed. Most of the participants had at least one car in their household. Dropout analyses on the participants' characteristics showed some selective dropout at the no exposure group for educational level ($\chi2$ =8.325, p=.004). Also, in the minimal exposure and no exposure group, the percentage of individuals reporting any/severe problems regarding mood was higher in the group that dropped out at T1, compared to the longitudinal sample (minimal exposure group: $\chi2$ =5.031, p=.025, no exposure group: $\chi2$ = 5.031, p=.040, respectively).

Table 1. Baseline characteristics of the sample.

	Total sample (n=642)	Maximal exposure (n=263)	Minimal exposure (n=179)	No exposure (n=200)
Socio-demographics				
Age (M (SD))	56.3 (16.1)	54.7 (16.2)	60.9 (13.4)*	54.2 (17.2)
Gender (% male)	46.2	42.4	47.5	50.0
Educational level (% higher educated)	52.5	55.6	48.0	52.5
Work status (% working)	54.8	57.3	47.7	57.7
Car ownership (% ≥ 1 car)	87.1	82.8	91.6	88.9
Health-related quality of life				
Mobility (% any or severe problems)	12.5	10.3	12.9	15.2
Self-care (% any or severe problems)	1.7	1.5	2.2	1.5
Daily activities (% any or severe problems)	11.1	11.1	9.0	13.1
Pain (% any or severe problems)	31.7	30.5	32.8	32.3
Mood (% any or severe problems)	11.5	10.7	12.4	11.8

Changes in total and transport-based PA – area-based exposure

At baseline, the average wear time ranged between 13.96 and 14.04 hours per day, and between 13.79 and 13.96 hours per day at follow-up (Table 2). The average number of wearing days ranged between 5.78 and 6.40 days at baseline and 5.64 and 6.34 at follow-up (data not shown). Within-group changes in wear time were not significant. In the maximal exposure group, the percentage of time spent in SB increased significantly between T0 and T1 (B=1.05, 95% CI 0.08; 2.01, p=.034), relating to 8.79 minutes per day. In contrast, for the minimal exposure group, the percentage of time spent in MVPA decreased significantly (B=-0.65, 95% CI -1.11; -0.20, p= .005). No changes were observed in the no exposure group. The wear time spent in transport ranged between 2.38 and 2.62 hours per day at baseline, and between 2.40 and 2.45 hours per day at follow-up. For the minimal exposure group, the wear time in transport decreased significantly (B=-0.18 95% CI 0.35; -0.01, p= .038). For the percentage of time in transport spent in SB, LPA and MVPA, a significant increase in SB and decrease in MVPA was found for the no exposure group (B=4.67, 95% CI 2.00; 7.34, p=.001, and B= -2.80, 95% CI -5.00; -0.60, p=.013, respectively). In absolute numbers, this relates to an average increase of 7.3 minutes per day of SB in transport, and an average decrease of 3.8 minutes per day of MVPA in transport. No changes were observed for the minimal and maximal exposure groups. Sensitivity analyses on the complete cases of this sample demonstrated similar trends (Supplementary material, Table S1).

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Average wear time spent on the Green Carpet increased significantly in the maximal exposure group from 2.67 minutes per day at baseline to 3.22 minutes per day at follow-up. The percentage of time spent in MVPA increased significantly from 12.29% at baseline to 21.09% at follow-up (B=8.80, 95% CI 1.18; 16.14, p= .024). The percentage of wear time at the Green Carpet spent in SB decreased, but this change was not significant. For the minimal exposure group, the average wear time spent on the Green Carpet was less than one minute and did not change over time. The percentage SB at the Green Carpet significantly decreased with 30%, from 71.07% to 41.85% (B=-29.85, 95% CI -49.57; -10.13, p=.003), and the amount of LPA increased with 34.01% (B=34.01, 95% CI 16.16; 51.86, p <.001).

Interactions between time x exposure group were determined to explore whether the changes over time were different for the three exposure groups (Table 3). In both the adjusted and unadjusted models, the change in transport-based SB was significantly different for the control group, compared to the maximal exposure group (B=-3.59, 95% CI -7.15; -0.02, p=.049) and minimal exposure group (B= -4.02, 95% CI -7.85, -0.19, p=.040) (Fig. 2). No significant interactions were found for the other total and transport-based PA outcomes.

Table 2. Observed (unadjusted) means with time as fixed factor and corrected for repeated measures in persons.

		Maximal exposure				Minimal exposure				No exposure			
Total PA		*n*	*Mean (SE)*	*B (95% CI)*	*p*	*n*	*Mean (SE)*	*B (95% CI)*	*p*	*n*	*Mean (SE)*	*B (95% CI)*	*p*
Wear time (hrs/day)	T0	263	13.96 (0.09)			179	14.04 (0.10)			200	13.96 (0.11)		
	T1	154	13.96 (0.11)	-0.01 (-0.23; 0.21)	.955	111	13.86 (0.12)	-0.18 (-0.43; 0.07)	.157	97	13.79 (0.16)	-0.17 (-0.48; 0.14)	.279
% SB	T0	263	**63.63 (0.54)**			179	64.29 (0.65)			200	64.30 (0.58)		
	T1	154	**64.68 (0.61)**	**1.05 (0.08; 2.01)**	**.034**	111	64.79 (0.77)	0.49 (-0.93; 1.92)	.495	97	64.80 (0.82)	0.49 (-1.11; 2.10)	.544
% LPA	T0	263	32.03 (0.52)			179	31.56 (0.61)			200	31.21 (0.58)		
	T1	154	31.26 (0.58)	-0.77 (-1.79; 0.24)	.135	111	31.71 (0.73)	0.16 (-1.20; 1.52)	.818	97	30.78 (0.74)	-0.43 (-1.86; 0.99)	.548
% MVPA	T0	263	4.33 (0.19)			179	**4.15 (0.23)**			200	4.48 (0.20)		
	T1	154	4.03 (0.24)	-0.30 (-0.76; 0.16)	.198	111	**3.49 (0.24)**	**-0.65 (-1.11; -0.20)**	**.005**	97	4.47 (0.27)	-0.01 (-0.51; 0.48)	.964
Transport-based PA													
Wear time in transport (hrs/day)	T0	263	2.50 (0.06)			179	**2.62 (0.08)**			200	2.38 (0.07)		
	T1	154	2.45 (0.08)	-0.05 (-0.22; 0.12)	.572	111	**2.44 (0.08)**	**-0.18 (-0.35; -0.01)**	**.038**	97	2.40 (0.09)	0.02 (-0.14; 0.18)	.797
% SB	T0	263	48.01 (0.89)			179	49.62 (1.05)			200	**45.57 (1.04)**		
	T1	154	48.89 (1.11)	0.88 (-1.41; 3.17)	.448	111	50.00 (1.21)	0.38 (-2.08; 2.84)	.760	97	**50.24 (1.36)**	**4.67 (2.00; 7.34)**	**.001**
% LPA	T0	263	35.54 (0.73)			179	35.17 (0.89)			200	35.27 (0.84)		
	T1	154	35.57 (0.81)	0.03 (-1.71; 1.78)	.971	111	36.14 (1.02)	0.97 (-0.99; 2.93)	.330	97	33.31 (0.94)	-1.96 (-4.14; 0.21)	.077
% MVPA	T0	263	16.48 (0.79)			179	15.20 (0.92)			200	**19.16 (1.02)**		
	T1	154	15.49 (0.92)	-0.99 (-2.84; 0.86)	.251	111	13.92 (1.11)	-1.28 (-3.48; 0.92)	.293	97	**16.36 (1.12)**	**-2.80 (-5.00; -0.60)**	**.013**

Table 2. Observed (unadjusted) means with time as fixed factor and corrected for repeated measures in persons. (continued)

		Maximal exposure				Minimal exposure				No exposure			
PA at Green Carpet													
Wear time at Green Carpet (min/day)	T0	263	**2.67 (0.80)**			179	0.16 (0.93)			200	0.018 (1.02)		
	T1	154	**3.22 (0.60)**	**2.65 (0.12; 5.19)**	**.040**	111	0.19 (0.75)	0.14 (-2.56; 2.85)	.918	97	0.006 (0.80)	n.a.	n.a.
% SB	T0	263	47.73 (4.38)			179	**71.70 (7.06)**			200	41.67 (29.10)		
	T1	154	37.30 (3.26)	-10.43 (-21.06; 0.21)	.055	111	**41.85 (7.22)**	**-29.85 (-49.57; -10.13)**	**.003**	97	100 (38.88)	n.a.	n.a.
% LPA	T0	263	39.89 (3.76)			179	**16.14 (6.09)**			200	58.33 (25.26)		
	T1	154	40.59 (3.24)	0.70 (-8.43; 9.83)	.880	111	**50.15 (7.15)**	**34.01 (16.16; 51.86)**	**.000**	97	<0.00 (28.85)	n.a.	n.a.
% MVPA	T0	263	**12.29 (3.09)**			179	12.63 (4.99)			200	<0.00 (20.68)		
	T1	154	**21.09 (2.68)**	**8.80 (1.18; 16.41)**	**.024**	111	8.65 (5.91)	-3.99 (-18.79; 10.81)	.596	97	<0.00 (32.04)	n.a.	n.a.

Table 3. Estimates of time x exposure group in unadjusted and maximal adjusted linear mixed effects models.

	Unadjusted model				Adjusted model*			
	Maximal vs. No exposure		Minimal vs. No exposure		Maximal vs. No exposure		Minimal vs. No exposure	
	B (95% CI)	*p*	*B (95% CI)*	*p*	*B (95% CI)*	*p*	*B (95% CI)*	*p*
Total PA								
% SB	0.68 (-1.13; 2.49)	.457	0.10 (-1.84; 2.04)	.920	0.92 (-0.92; 2.75)	.326	0.24 (-1.74; 2.22)	.809
% LPA	-0.38 (-2.12; 1.36)	.667	0.54 (-1.32; 2.41)	.567	-0.64 (-2.41; 1.12)	.472	0.44 (-1.46; 2.34)	.647
% MVPA	-0.27 (-0.94; 0.40)	.427	-0.62 (-1.34; 0.09)	.088	-0.28 (-0.96; 0.40)	.423	-0.69 (-1.43; 0.04)	.065
Transport-based PA								
% SB	**-3.82 (-7.29; -0.35)**	**.031**	**-4.24 (-7.96; -0.53)**	**.025**	**-3.59 (-7.15; -0.02)**	**.049**	**-4.02 (-7.85; -0.19)**	**.040**
% LPA	1.96 (-0.77; 4.70)	.159	2.75 (-0.18; 5.69)	.066	1.69 (-1.12; 4.49)	.238	2.91 (-0.11; 5.93)	.058
% MVPA	1.76 (-1.15; 4.66)	.236	1.50 (-1.62; 4.61)	.345	1.81 (-1.17; 4.79)	.234	1.15 (-2.06; 4.35)	.482

*= adjusted for age, gender, educational level, work status, car ownership and health-related quality of life; PA= Physical activity; SB= sedentary behavior; LPA= light physical activity; MVPA= moderate-to-vigorous physical activity; B= Beta coefficient; 95% CI; 95% confident interval

Changes in total and transport-based PA – actual users

When focusing on individuals that actually used the Green Carpet versus individuals that did not use the Green Carpet, we found a significant decrease in wear time over time in both groups (Table 4). In both groups, no significant changes were found in the total percentage of SB, LPA and MVPA. Also, the total amount of time spent in transport remained the same in both groups, and the percentage transport-based SB and LPA did not significantly change over time. For the group that did not use the Green Carpet area, the total percentage of transport-based MVPA decreased significantly (B=-1.78, 95% CI -3.43; -0.12, p=.035) (5.70 minutes/day) while the percentage of MVPA remained stable in the group of individuals that actually used the Green Carpet. No significant changes were found in the wear time or physical activity levels on the Green Carpet. In both the adjusted and unadjusted models, the interactions between time x exposure were not significant for any of the PA outcomes (Table 5).

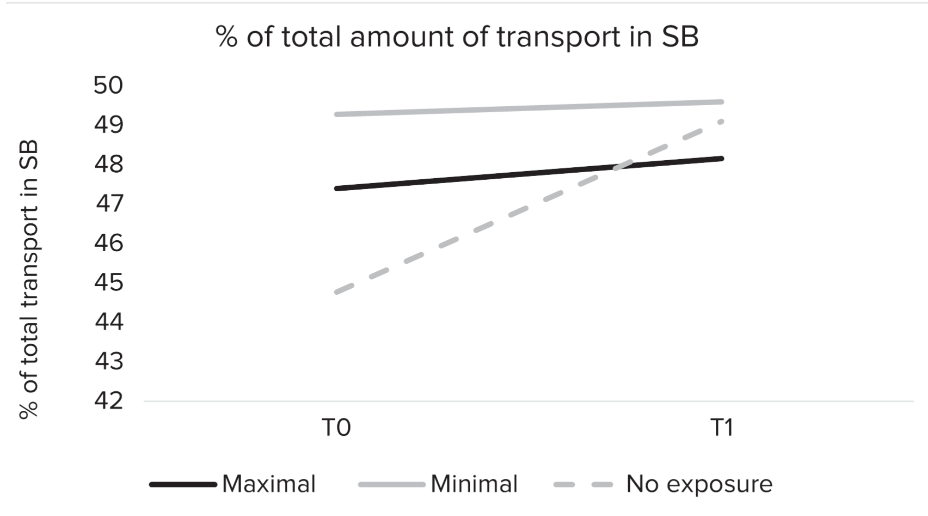

Figure 2. Visual representation of the time x exposure group interaction for the transport-based SB outcome

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Table 4. Observed means with time as fixed factor and corrected for repeated measures in persons, comparison of users and non-users the Green Carpet area.

		Users (n=108)			Non-users (n=208)		
Total PA		*Mean (SE)*	*B (95% CI)*	*p*	*Mean (SE)*	*B (95% CI)*	*p*
Wear time (hrs)	T0	**14.35 (0.10)**			**14.14 (0.10)**		
	T1	**14.11 (0.12)**	**-0.24 (-0.47; -0.01)**	**.040**	**13.87 (0.10)**	**-0.27 (-0.49; -0.06)**	**.011**
% SB	T0	63.32 (0.78)			65.32 (0.55)		
	T1	64.44 (0.81)	1.11 (-0.00; 2.22)	.050	65.37 (0.60)	0.050 (-1.00; 1.10)	.925
% LPA	T0	30.73 (0.53)			32.25 (0.73)		
	T1	30.96 (0.56)	-0.85 (-1.95; 0.25)	.127	31.40 (0.76)	0.23 (-0.75; 1.21)	.644
% MVPA	T0	4.43 (0.27)			3.95 (0.21)		
	T1	4.17 (0.25)	-0.26 (-0.70; 0.18)	.241	3.67 (0.20)	-0.28 (-0.62; 0.059)	.105
Transport-based PA							
Wear time (hrs)	T0	2.63 (0.08)			2.47 (0.07)		
	T1	2.55 (0.08)	-0.09 (-0.27; 0.10)	.347	2.42 (0.07)	-0.06 (-0.17; 0.06)	.343
% SB	T0	48.21 (1.42)			49.14 (1.00)		
	T1	48.55 (1.34)	0.34 (-2.32; 3.00)	.802	50.72 (0.99)	1.58 (-0.38; 3.53)	.114
% LPA	T0	35.14 (1.08)			34.63 (0.84)		
	T1	35.34 (1.01)	0.20 (-1.82; 2.22)	.847	34.83 (0.75)	0.20 (-1.42; 1.82)	.808
% MVPA	T0	16.65 (1.19)			**16.23 (0.94)**		
	T1	16.12 (1.16)	-0.53 (-2.52; 1.45)	.596	**14.46 (0.86)**	**-1.78 (-3.43; -0.12)**	**.035**

Table 4. Observed means with time as fixed factor and corrected for repeated measures in persons, comparison of users and non-users the Green Carpet area. (continued)

		Users (n=108)			Non-users (n=208)		
PA at Green Carpet							
Wear time (min)	T0	150.15 (56.14)					
	T1	133.88 (26.79)	-16.27 (-124.22; 91.67)	.767			
% SB	T0	44.80 (5.11)					
	T1	37.83 (3.96)	-6.97 (-19.32; 5.39)	.266			
% LPA	T0	43.93 (4.42)					
	T1	42.93 (3.93)	-1.00 (-11.61 ; 9.60)	.851			
% MVPA	T0	11.22 (3.49)					
	T1	18.99 (3.29)	7.77 (-0.85; 16.39)	.077			

PA= physical activity; SB= sedentary behavior; LPA= light physical activity; MVPA= moderate-to-vigorous physical activity; SE= standard error; B= beta coefficient; 95% CI= 95% confidence interval

Table 5. Estimates of time x exposure group in unadjusted and maximal adjusted linear mixed effects models.

	Unadjusted model		**Adjusted model**	
	Users vs. Non-users		Users vs. Non-users	
Total PA	*B (95% CI)*	*p*	*B (95% CI)*	*p*
% SB	1.06 (-0.59; 2.72)	.206	1.19 (-0.51; 2.89)	.169
% LPA	-1.08 (-2.66; 0.49)	.176	-1.24 (-2.86; 0.37)	.130
% MVPA	0.02 (-0.55; 0.58)	.948	0.05 (-0.53; 0.63)	.865
Transport-based PA				
% SB	-1.24 (-4.55; 2.07)	.462	-0.76 (-4.20; 2.68)	.664
% LPA	-0.00 (-2.67; 2.66)	.998	-0.49 (-3.26; 2.27)	.726
% MVPA	1.24 (-1.45; 3.94)	.365	1.25 (-1.54; 4.05)	.379

*= adjusted for age, gender, educational level, work status, car ownership and health-related quality of life; PA= Physical activity; SB= sedentary behavior; LPA= light physical activity; MVPA= moderate-to-vigorous physical activity; B= Beta coefficient; 95% CI; 95% confident interval.

DISCUSSION

The aim of this study was to evaluate changes in overall and transport-based PA and SB of people living near an area of major infrastructural change and to compare it with transport-based PA changes in individuals living further away. In addition, we evaluated the differences in total PA outcomes for individuals who were actually using the new infrastructure and those who were not.

For the total PA levels, we found a decrease in the percentage MVPA in the minimal exposure group (5.9%, 5.94 minutes/day) and an increase in the percentage of SB (0.3%, 8.8 minutes/day) in the maximal exposure group. The PA levels in the control group did not significantly change over time. For both the adjusted and unadjusted models, the trends in total PA over time did not differ across the three groups. Some previous studies also found decreased levels of MVPA across study groups, at short-term follow-ups [65, 70]. As the sample in the minimal exposure group was significantly older compared to the others, the decrease in the unadjusted MVPA levels might be an age-related decline [197].

For transport-based PA levels, we found a decrease in the percentage MVPA (2.8%; -3.8 minutes/day) and an increase in the percentage SB for the no exposure group (4.7%; 7.3 minutes/day), while for the maximal and minimal exposure group the levels of transport-based SB and MVPA did not change over time. However, it should be noted that baseline levels of transport-based MVPA were higher in the no exposure group compared to the other areas. The decrease might be an adaptation to MVPA levels that are more

comparable to the average. Also, although the participants in the no exposure group were not exposed to the Green Carpet, some smaller scale environmental changes have been going on in Heerlen. During this first follow-up measurement, the main railway station and its surroundings were under construction, and the parking costs of some parking spaces in the city center were reduced to make visiting the inner city more attractive. However, it is unclear if and to what extent this impacted on the study results. Longer-term follow-ups are necessary to see if this trend continues.

Although the total and transport-based PA levels did not increase over time, we found an 8% increase of MVPA on the Green Carpet. This implies that when participants were on the Green Carpet, they more often were moderate-to-vigorously active. As the Green Carpet was only a transport route at the time of follow-up, this increase in MVPA and the increase of time spent in this area probably relates to an increase in brisk walking or cycling. For the minimal exposure group, we found a decrease in SB and increase of LPA on the Green Carpet. Given the distance to the Green Carpet and the PA levels of the participants of this group, this change might indicate that the Green Carpet led to relatively less car use and more light-active forms of PA, such as cycling. Hereby, the Green Carpet might act as a route for active trips that were previously made using a car or public transport. These results indicate that the Green Carpet evokes behavioral changes at the Green Carpet, but this did not yet lead to additional PA.

Lastly, we compared users and non-users of the Green Carpet area. For individuals that used the Green Carpet, no changes were observed in transport-based PA, while in the non-user group, transport-based MVPA decreased by 1.8%. Although this difference is slightly smaller compared to the changes in area-based exposure groups, the trends over time were comparable. This means that, possibly, the changes between the area-based groups might reflect the differences between visiting and non-visiting/ using individuals. This would imply that living in a Green Carpet area prevented a decrease in transport-based MVPA only for actual users. However, even though we adjusted for several covariates, more in-depth analyses are needed to reduce the possible influence of selective daily mobility bias in the use of the Green Carpet [198]. Previous research showed that users of new infrastructures might be the more active individuals [170], but our results did not suggest that this was an issue in our study. Further, the time x exposure interaction was not significant. Thus, although there was a significant decrease in transport-based PA in the non-visiting group, the trend over time did not differ between users and non-users of the Green Carpet. Moreover, the changes in PA levels at the Green Carpet were of a same magnitude compared to the area-based exposure groups, but were not statistically significant. Remarkably, the average wear time while in the Green Carpet showed an opposite trend in the user groups, compared to the areabased study groups. Probably, this is due to the increased connectivity of the area and the removal of traffic lights that caused major traffic jams.

Although we did not find increases in transport-based PA, we found that individuals in the exposed areas, on average, did not decrease the amount of transport-based MVPA, in contrast to the control area. In two systematic reviews it was argued that, in general, studies were able to detect positive behavioral changes when the follow-up measurement took place at least 6-12 months after the opening of the new infrastructure [29, 30]. In this study, the average time between the opening of the Green Carpet and the follow-up measurement was 9.8 months, with a median of 10.5 months. Therefore, more follow-up measurements are necessary to investigate the longer-term effects of this infrastructural change on PA behavior. Since the construction of dwellings and facilities is still ongoing until 2026 and the planted trees need time to grow to become a more attractive place for leisure time PA, longer-term assessments are warranted.

In the current study, we focused on the general effects of an infrastructural change to the built environment on PA, whereby we adjusted for several covariates, but did not consider possible subgroup effects. As proposed by theoretical models, individual-level socioeconomic, cultural and demographic characteristics might moderate the effect of the environment on PA [142]. Also, individuals' perceptions of the environment might mediate this relationship between environment and behavior, but this was not taken into account in this study [199]. Additional analyses are needed to further investigate the effects of individual-level moderating and mediating factors.

Strengths of this study are its longitudinal character, large-scale device-based measurements, and the inclusion of sub analyses on users and nonusers of the Green Carpet, next to area-based exposure measures. To our knowledge, this is the first study on this scale that uses both GPS and accelerometers in a longitudinal approach to investigate effects of an infrastructural project on PA behavior, which improves the validity and reliability of studies into the relationship between environment and behavior.

An important limitation of this study is the possible misclassification of the datapoints that were classified as 'in transport'. Giving the positive predictive value of 74.9%, the algorithm is slightly susceptible to false positives. This means that some of the 60-second time periods might be classified as trips, while they are not [177]. Another limitation of this study is the dropout of participants between baseline and follow-up measurements, due to several reasons. The persons that dropped out spent slightly more time in MVPA at baseline. As these models provide the opportunity to handle missing outcome data based on valid covariates on baseline, these data emphasized the importance of using

linear mixed models. However, sensitivity analyses showed that the findings were similar for the sample that contained only complete baseline and follow-up measurements. Also, the percentage of people that were lower educated and experiencing problems regarding mood was significantly higher in the dropout group, compared to the longitudinal sample. Thus, sensitivity analyses did not reveal significant differences in the outcome measures between the dropout group and longitudinal sample, nor between lower and higher educated individuals and people with or without problems regarding mood.

Further, when interpreting the results of this study, the relative nature of the data should be noted. The average weartime of the devices was about 14 hours per day, whereby consequently about 10 hours of the day were not recorded. Although a significant part of these hours is expected to be sleep time, these hours partially consist of non-weartime during the day. In both cases, we did not correct for this in the current analyses. Also, as a day consists of 24 hours, an increase in the total time in one behavior (SB, LPA or MVPA) causes a decrease in the total time spent in on or more of the other domains [200]. Compositional data analyses (CoDa) accounts for this codependency by handling a 'time budget' of 24 hours per day, of which time is allocated to specific behaviors or physical activity domains. Previous research has shown how this type of analyses might help to further understand patterns of physical activity behaviors during the day [201], or examine the combined effects of sleep, SB, LPA and MVPA on health outcomes [202]. Hereby, CoDa provides opportunities for future research. Lastly, the recruited group was older and higher educated than the total population in the selected areas. Despite controlling for these covariates in the statistical models, results might be less generalizable to a younger and lower educated sample.

CONCLUSION

This study showed that tunneling a highway passing through residential areas of Maastricht city, and reconstructing the new open space in favor of non-motorized and slow traffic did not significantly increase total or transport-based PA, within a year after opening in 2018. However, the amount of transport-based MVPA showed a stable trend over time in the exposure groups, in contrast to the control group. The percentage MVPA at the Green Carpet area increased significantly for individuals from the maximal exposure group. For the minimal exposure group, the percentage of time spent in SB when being at the Green Carpet decreased, while LPA increased significantly. This implies that the PA patterns within the Green Carpet area changed over time, but did not yet lead to an increase in the total volume of PA. Although the results differed between the area-based exposure and individual-level exposure analyses, the trends were similar for both analyses. This suggests that areabased differences might reflect the differences between users and nonusers of the Green Carpet. Due to possible interference of selective mobility bias, however, the results should be interpreted carefully. Further, this paper reflects that the relationship between infrastructure and PA is not unambiguous, as it depends on the context, and thereby interacts with the contextual factors in the larger ecosystem. Finally, to investigate longer-term effects, more research is needed.

APPENDIX

Supplementary file 1

Sensitivity analyses on longitudinal data

Table S1. Observed means with time as fixed factor and corrected for repeated measures in persons – longitudinal data only.

		Maximal exposure (N=154)			Minimal exposure (N=111)			No exposure (N=97)		
Total physical activity		*Mean (SE)*	*B (95% CI)*	*p*	*Mean (SE)*	*B (95% CI)*	*p*	*Mean (SE)*	*B (95% CI)*	*p*
% SB	T0	63.78 (0.68)			64.97 (0.83)			65.11 (0.75)		
	T1	**64.90 (0.70)**	**1.13 (0.12; 2.13)**	**.028**	65.08 (0.67)	0.10 (-1.40; 1.61)	.894	65.08 (0.88)	-0.03 (-1.72; 1.66)	.970
% LPA	T0	31.93 (0.64)			31.05 (0.78)			30.82 (0.73)		
	T1	31.18 (0.65)	-0.74 (-1.78; 0.29)	.157	31.51 (0.82)	0.46 (-0.97; 1.90)	.525	30.67 (0.80)	-0.14 (-1.64; 1.35)	.850
% MVPA	T0	4.29 (0.24)			3.97 (0.29)			4.07 (0.31)		
	T1	3.91 (0.24)	-0.38 (-0.77; 0.14)	.059	**3.42 (0.27)**	**-0.55 (-1.04; -0.07)**	**.025**	4.25 (0.32)	0.18 (-0.35; 0.70)	.507
Transport domain										
% SB	T0	49.23 (1.23)			50.49 (1.36)			46.26 (1.56)		
	T1	49.60 (1.22)	0.37 (-2.12; 2.86)	.770	49.95 (1.34)	-0.54 (-3.22; 2.15)	.693	**50.38 (1.53)**	**4.11 (1.17; 7.06)**	**.007**
% LPA	T0	34.53 (0.94)			34.64 (1.16)			35.15 (1.24)		
	T1	35.19 (0.87)	0.66 (-1.24; 2.57)	.494	35.96 (1.14)	1.31 (-0.80; 3.43)	.222	33.37 (1.02)	-1.78 (-4.33; 0.76)	.167
% MVPA	T0	16.27 (1.03)			14.87 (1.24)			18.63 (1.55)		
	T1	15.23 (1.01)	-1.05 (-2.91; 0.82)	.270	14.07 (1.26)	-0.80 (-3.23; 1.63)	.516	16.22 (1.31)	-2.40 (-4.87; 0.06)	.056

PA= physical activity; SB= sedentary behavior; LPA= light physical activity; MVPA= moderate-to-vigorous physical activity; n= sample size; SE= standard error; B= beta coefficient; 95% CI= 95% confidence interval.

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CHAPTER 7

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.

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 [203]. 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 [204]. 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 [205]. 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 [206].The availability of trails and community gardens, and walkability and bike ability are mentioned as health assets of the built environment [207]. The relevance of the built environment as a determinant of population health is expressed by multiple socioecological frameworks [16, 111]. The built environment can affect health and wellbeing via several factors, such as neighborhood and housing conditions, safety (from traffic and crime), and toxins [111]. 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 [20]. 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 [208-210].

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 [29-31]. Also, personal factors such as sociodemographics, personality and physiological factors may moderate the relationship between environment and behavior [20, 211], 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 [62]. 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 [212]. In addition, Smith and colleagues found some indications that improvements in infrastructure might predominantly benefit socioeconomically advantaged groups [15]. 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 [213]. 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 [214]. 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 [215]. 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 [189].

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 [30]. More extensive interventions typically imply major changes to the entire system [216]. 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 [89]. 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 [217, 218]. 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 [219]. 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.

METHODS

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 [196]. Images pre- and post-reconstruction are available in appendix 1.

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 [219]. 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. 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).

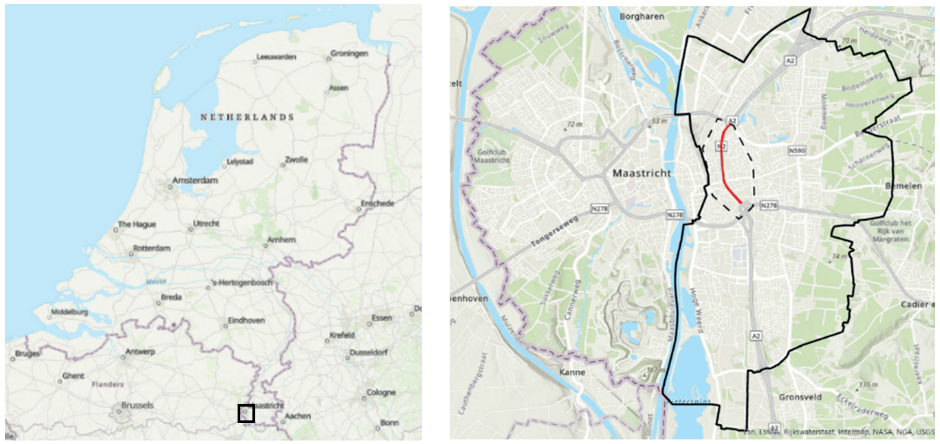

Figure 1. Left: Location of the city of Maastricht, in the south of The Netherlands; Right: East Maastricht area in black, with reconstructed area in dashed line and in red the highway section that was tunneled.

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.

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% [177]. 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).

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) [147]. 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.

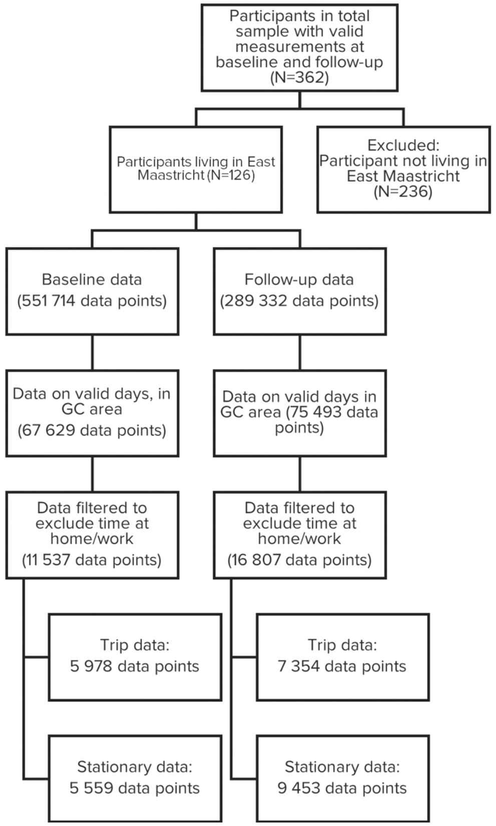

Figure 2. Flowchart data inclusion; GC= Green Carpet.

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 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 [220]. 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.

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 [166] and stratified analyses were performed to visualize the significant interactions.

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

RESULTS

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.

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 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

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)			Lower educated (N=55)			Higher educated (N=71)		
	Baseline	Follow-up	*p*	Baseline	Follow-up	*p*	Baseline	Follow-up	*p*
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)*	16.72 (11.66)	0.137	14.64 (10.84)	14.24 (11.51)	0.935

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

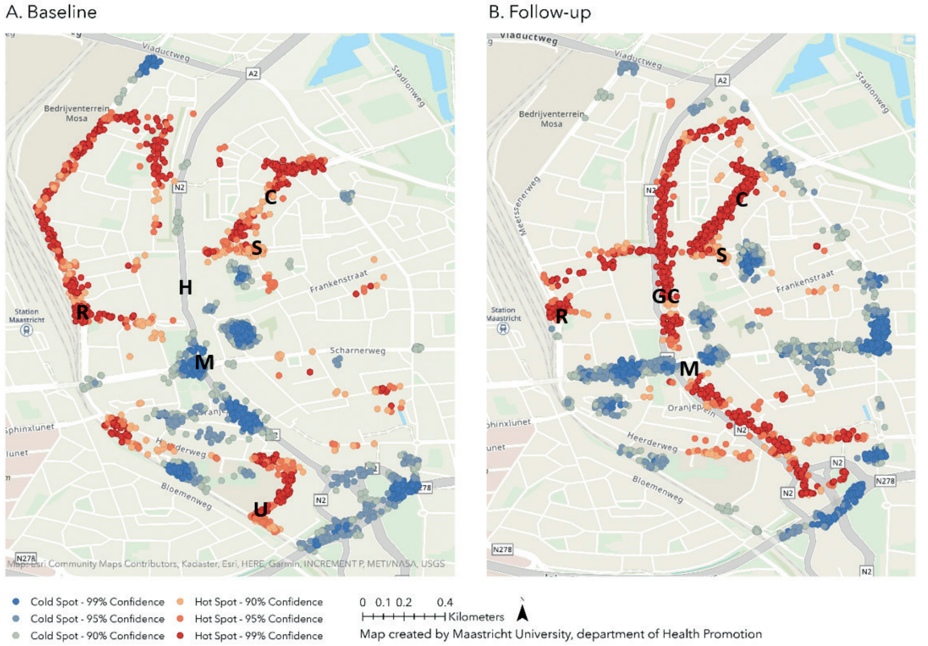

Figure 3. Results of optimized hot spot analysis – trip data; C=connecting street between shopping center and sports facilities/park; S= shopping center; H= former highway; M= horizontal street; GC= Green Carpet; U= connection to university/hospital.

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.

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.

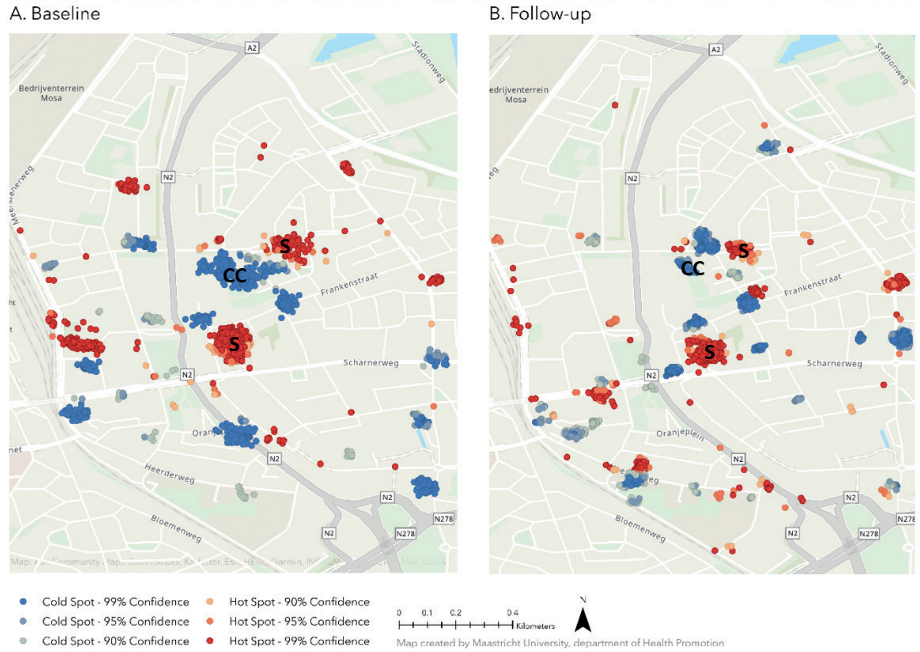

Figure 4. Results of optimized hot spot analysis – stationary data. S= shopping center; CC = community center.

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 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.

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 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.

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

	% transport-based SB†				% Transport-based LPA†				% Transport-based MVPA†			
	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			*				*				*	
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	

† Corrected for use of the Green Carpet at baseline; *= excluded from regression analyses; GC= Green Carpet; SB= Sedentary behavior; LPA= light physical activity; MVPA = moderate-to-vigorous physical activity; β= standardized beta; p= statistical significance.

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

	% SB†				% LPA†				% MVPA†			
	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	

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

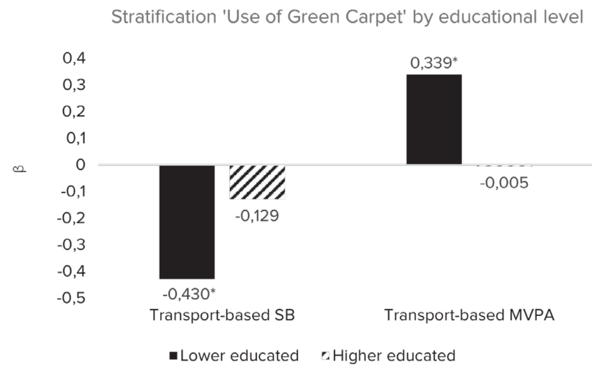


Figure 5. Interactions between educational level and the use of the Green Carpet at follow-up, for transport-based SB and MVPA; *=p<0.05.

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 [15]. 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 [172]. 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 [221]. 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 [222]. 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 associated with the use of active transport [223, 224]. 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 [225].

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 [226]. For example, it is known that the amount of traffic and the quality of paths can influence route choice for active transport [227]. 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 [195]. 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 [228]. 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 [29, 30]. More recent research suggests that it might take even more than three years to detect behavioral change after large-scale infrastructural interventions [213].

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 [92, 229]. 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 [92]. However, the existence of such ActivityStat is the subject of debate among researchers and clear evidence is lacking [229]. 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 [223, 230]. 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 [231]. 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 [170]. 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 [142]. 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 [232]. 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.

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.

APPENDIX

Supplementary material

Figure S1.a. Picture of the reconstructed area when highway A2 was crossing the city of Maastricht, before the opening of the tunnel and the Green Carpet. Source: Projectbureau A2 Maastricht

Figure S1.b. Picture of the Green Carpet showing the profile consisting of a semi-paved middle path, adjacent one-way streets, and green strips separating them. Source: Projectbureau A2 Maastricht/ Fred Berghmans.

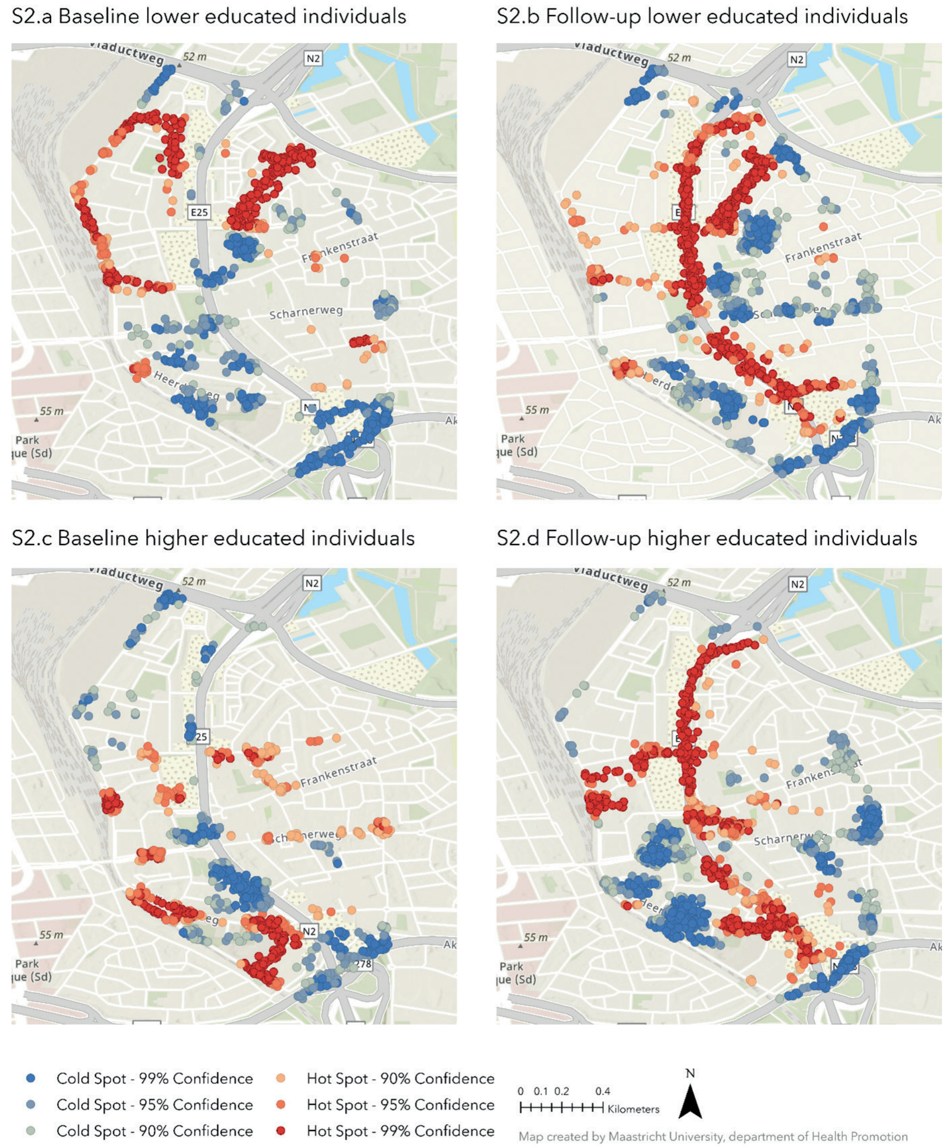
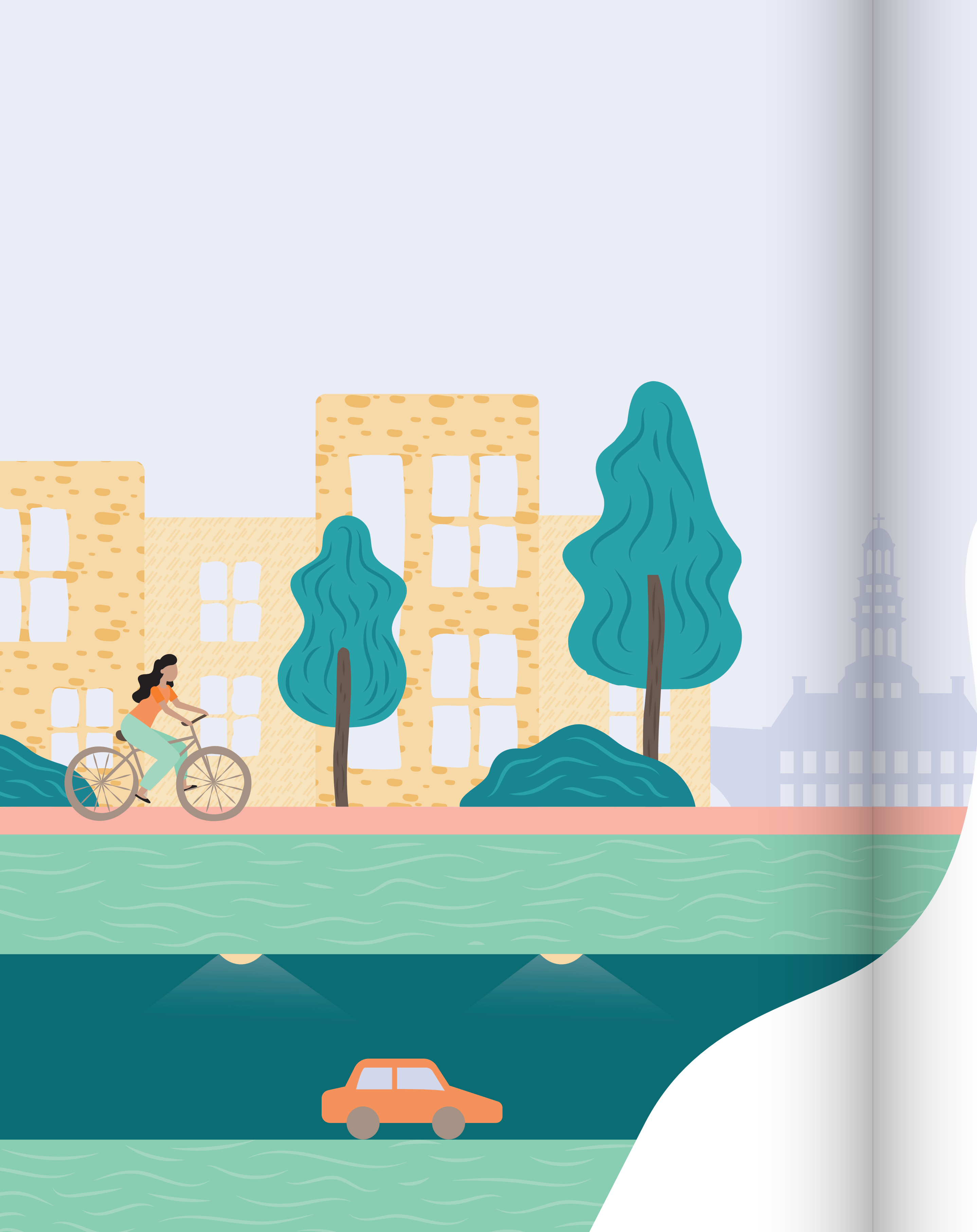


Figure S2.a through d. Hot spot analyses on trip data, stratified for educational level.



CHAPTER 8

Effects of major urban redesign on sedentary behavior, physical activity, active transport and health-related quality of life in adults.

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ABSTRACT

The built environment is increasingly recognized as a determinant for health and health behaviors. Existing evidence regarding the relationship between environment and health (behaviors) is varying in significance and magnitude, and more high-quality longitudinal studies are needed. The aim of this study was to evaluate the effects of a major urban redesign project on physical activity (PA), sedentary behavior (SB), active transport (AT), health-related quality of life (HRQOL), social activities (SA) and meaningfulness, at 29-39 months after opening of the reconstructed area. PA and AT were measured using accelerometers and GPS loggers. HRQOL and sociodemographic characteristics were assessed using questionnaires. In total, 241 participants provided valid data at baseline and follow-up. We distinguished three groups, based on proximity to the intervention area: maximal exposure group, minimal exposure group and no exposure group. Both the maximal and minimal exposure groups showed significantly different trends regarding transport-based PA levels compared to the no exposure group. In the exposure groups SB decreased, while it increased in the no exposure group. Also, transport-based light intensity PA remained stable in the exposure groups, while it significantly decreased in the no exposure group. No intervention effects were found for total daily PA levels. Scores on SA and meaningfulness increased in the maximal exposure group and decreased in the minimal and no exposure group, but changes were not statistically significant. The results of this study emphasize the potential of the built environment in changing transport-based SB and PA and highlights the relevance of longer-term follow-up measurements to explore the full potential of urban redesign projects.

INTRODUCTION

Over the past decades, the built environment is increasingly recognized as a determinant of health and health behaviors. Several socioecological models explain how changes in the environment can lead to improved health at the individual-level through changes in the organizational, intrapersonal and interpersonal level of influence [12, 17, 18]. Systematic reviews show that the built environment can affect health behaviors such as physical activity, active transport and healthy eating, both in the entire population [29, 189], and in subgroups in society [212, 233]. However, the effects are varying in significance and magnitude [30, 31].

Physical activity is considered to be one of many pathways between the environment and health and well-being [234]. Other pathways that were identified were for example community interaction, healthy eating, social relationships, leisure and work [235]. Also, air quality is found to be significantly correlated with quality of life and life satisfaction [236, 237]. An extensive amount of research concerning the relationship between the environment and health assesses the effect of green space on general and mental health [238, 239]. Most studies indicate that there is a beneficial relationship between green space and health, but the evidence is weak [238]. This was confirmed by a review that evaluated the effects of improving green infrastructure and urban regeneration on mental health and well-being in adults, which only found weak evidence for the relationship between the built environment and quality-of-life [240].

The inconclusive results of previous studies are due to several factors. For research on the relationship between environment and physical activity, one of the main shortcomings of existing research is the relatively short follow-up term [29, 30]. While in many natural experimental studies the time between exposure and follow-up is less than 24 months, behavioral change might take more than 3 years to actually occur [213]. Especially in large projects, several external factors can influence follow-up times, for example delays in implementation of urban redesign plans or the typical short duration of research contracts and projects [241]. This lack of longer-term follow-up studies is unfortunate, especially since in some interventions, evidence may accumulate over time to show the strength of their outcomes [242]. For research regarding the relationship between the built environment and general health and wellbeing, a large number of existing studies are based on cross-sectional analyses, which makes it difficult to explore causal relationships, and the risk of bias was considered to be serious in the majority of the studies [240]. Lastly, a recent review of reviews concluded that future research should focus on improving study quality, for example by using longitudinal methods and novel technologies such as GPS- data and ecological momentary assessments [243].

An opportunity to design a high-quality longitudinal natural experiment assessing the effects of the built environment on both physical activity levels and health-related quality of life presented itself with a major urban highway redesign project running through the Dutch city of Maastricht (a city in The Netherlands) . This longitudinal natural experiment lasted for six years, of which the last follow-up measurement took place 29-39 months after the official opening of the new tunnel infrastructure in December 2016. Hereby, the current study aims to evaluate the longer-term effects of a major infrastructural redesign project on the physical activity levels and self-reported health-related quality of life of adults. To our knowledge, this is one of the first large-scale longitudinal studies that used device-based measurements and a follow-up time of at least 2 years after opening of the newly designed area.

METHODS

Green Carpet

In 2016, a crosstown highway was tunneled and the space on top of this tunnel was redesigned and included new infrastructure, houses and commercial spaces (www.mijngroeneloper.nl). The new infrastructure has a length of 2.3 km and consists of a semi-paved middle path prioritized for pedestrians, bicyclists and recreation, accompanied by one-way streets for slow local traffic at both sides of the path. The middle path is separated from the one-way streets by trees and greenery, creating the so-called Green Carpet (www.mijngroeneloper.nl). The Green Carpet was officially opened in April 2018 and the construction of houses and commercial spaces started right after but is still ongoing until 2026.

Design of the experiment

The design of this study is a natural experiment with three exposure groups, based on the proximity to the newly constructed area. Participants were adults (≥18 years) who are able to walk without walking aids, and able to fill out a Dutch questionnaire (with or without help). The participants in the maximal exposure group (living in neighborhoods bordering the Green Carpet) and the minimal exposure group (living in other parts of the same city) are expected to be more or less exposed to the intervention, respectively. Participants in the no exposure group lived in a different city in the same region and were not expected to be exposed to the newly designed area. All participants were measured at three points in time: baseline (T0; July 2016 – July 2017), follow-up I (T1; July 2018 – July 2019) and follow-up II (T2; September 2020 – July 2021) (Figure 1). During the second follow-up, measurements were paused between the 18th of December 2020 and 1st of April 2021 to comply with COVID-19 regulations. The experiment was registered at the Netherlands Trial Register (NL8108). After review of the study protocol, the medical ethical committee

of the Maastricht University Medical Center (MUMC+) decided that formal ethical approval was not required (METC 16-4-109).

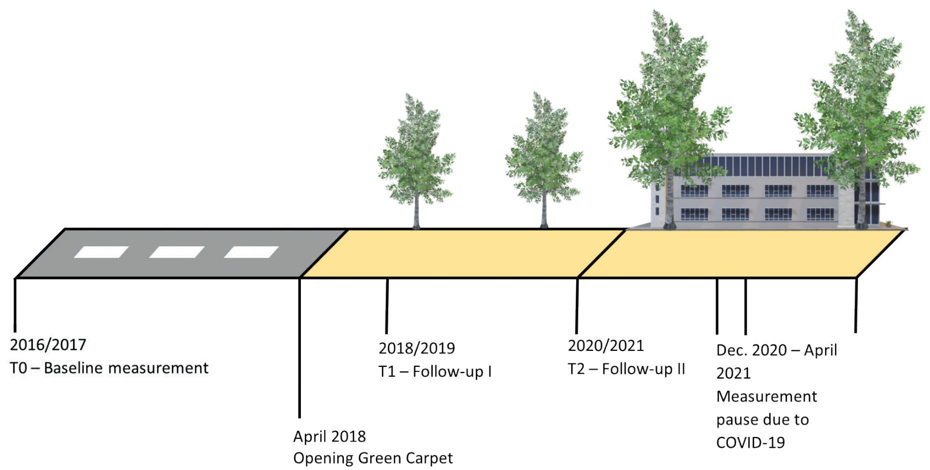

Figure 1. Timeline of natural experiment

Measurements

Sociodemographic characteristics

Age, gender, educational level, work status and car ownership were assessed using a questionnaire. Gender was dichotomized in male (0) and female (1). Educational level was assessed following the ISCED 2011 guidelines [244]. To create equal groups, participants with basic and intermediate levels of education were merged into the lower educated group (0) and individuals with a degree at a university of applied sciences or higher were merged in the higher educated group (1). Work status (0= not employed, 1= employed) and car ownership (0= no car in household, 1= one or more cars in household) were also dichotomized to create dummy variables for further analyses.

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Health-related quality of life

Health-related quality of life was measured using the EQ-5D-3L questionnaire, which assesses five domains of health (mobility, self-care, daily activities, pain and mood) on three levels (no problems, any problems, severe problem) [148]. Due to the homogeneity of the relatively healthy sample, scores were coded as 0 (experiencing no problems) and 1 (experiencing any problems). Further, the total score was calculated based on the country-specific value sets that are available for this questionnaire (Janssen et al., 2019). Two additional subscales were added to evaluate social activities and meaningfulness. The subscales consisted of items that were scored on a five-point scale ranging from totally disagree to totally agree. For social activities, two items were included, 1) '*I regularly* *participate in activities in my neighborhood*', and 2) '*I have many friends/acquaintances in my neighborhood*'. For the subscale meaningfulness, three items were included, 1) '*I feel in control of my life*' , 2) '*I have a future perspective in my life*', and 3) '*I pursue goals and ideals in my life*'. For both subscales, total scores were calculated by summing the scores on the individual items. The internal validity of the subscales was acceptable to good (α=0.613 and α=0.837, for social activities and meaningfulness, respectively).

Physical activity, sedentary behavior and active transport

Physical activity and active transport were assessed using an accelerometer (Actigraph GT3X+) and GPS-logger (Qstarz BTQ1000XT). The devices were worn for 6 consecutive days using an elastic band on the hip. The devices had to be taken off at night to charge the battery of the GPS-logger, and during water activities (i.e. showering, swimming) and contact sports to prevent damage.

The accelerometer recorded data with epochs of 10s and the GPS-logger with epochs of 15 seconds. HABITUS was used to filter, convert and merge the datasets into 60s epochs (www.habitus.eu). Freedson 1998 cut off points were used to distinguish between sedentary behavior (SB; 0-100 counts per minutes (cpm)), light intensity physical activity (LPA) and moderate-to-vigorous intensity physical activity (MVPA) [147]. Periods of more than 60 minutes of 0 cpm were regarded as non-wear time. Datapoints were marked as being part of a trip or being stationary based on the speed and distance between two consecutive epochs. If the distance between two consecutive points was ≥100 meters and the duration exceeded 120 seconds, data were marked as a trip. A stop of at least 120 seconds at one location was marked as a pause point and a pause of more than 180 seconds was marked as the endpoint of a trip. The trip detection algorithm had an accuracy of 92.5% [245]. Datapoints that were part of a trip were selected to determine transport-based SB, LPA and MVPA. All datapoints were selected to determine total physical activity levels.

Statistical analyses

All statistical analyses were performed in SPSS version 27 (IBM Corp., Armonk, NY, USA). Descriptive statistics were used to describe sample characteristics. T-tests and chi-square tests were performed to explore between-group differences in all covariates. T-tests and one-way ANOVA were used to examine between-group differences in outcome measures. Paired-samples T-tests were used to test within-group differences between baseline and follow-up. To test intervention effects, we used linear mixed models. This type of statistical models accounts for repeated measures within individuals, and is able to handle missing data in a longitudinal sample, using the values of covariates at baseline. For each outcome measure, a model was composed. Time was entered as a fixed factor

and we accounted for repeated measures within persons. Each model was adjusted for age, gender, educational level, work status, and car-ownership. The models were supplemented with an interaction term between time x area-based exposure group to explore intervention effects. For all statistical analyses, a p-value of 0.05 was used as threshold for statistical significance.

RESULTS

Description of the sample

In total, 241 participants provided valid data at baseline and follow-up which corresponds to a response rate of 38% at follow-up II. Sensitivity analyses showed that drop-outs were significantly younger (t= 3.624, p<.001) and less often a car owner (X^2= 7.648, p=.006). Of these participants, 105 were part of the maximal exposure group, 80 of the minimal exposure group and 56 participants we part of the no exposure group. The mean age of the sample was 59.8 years (SD = 12.8). The mean age of the minimal exposure groups was significantly higher than the mean age of the maximal exposure group (t=2.367, p=.019) and the no exposure group (t=2.429, p=.016). About half of the sample was male and about half of the sample was employed (45.9%). In total, 90.5% of the sample had access to at least one car in their household. No association was found between the exposure group and gender (X^2=1.752, p=.417), educational level (X^2=3.869, p=.145) work status (X^2=2.981, p=.225) or car ownership (X^2=0.410, p=.815).

Table 1. Baseline characteristics of longitudinal sample

	Total sample (N=241)	Maximal exposure (N=105)	Minimal exposure (N=80)	No exposure (N=56)
Age (mean (SD))	59.8 (12.8)	58.5 (12.6)	62.6 (12.0)*	57.6 (13.9)
Gender (% male)	52.3	58.1	46.3	50.0
Educational level (% higher educated)	53.7	50.5	49.4	66.1
Work status (% working)	45.9	48.6	38.3	51.8
Car ownership (% having ≥ 1 car in household)	90.5	88.6	91.4	92.9

* = significantly different from age in maximal and no exposure groups.

Physical activity and active transport

For the maximal exposure group, the percentage of total and transport-based physical activity levels did not significantly change over time. In absolute terms, the amount of

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transport-based SB decreased with 11.58 minutes (t=-2.728, p=.007). In the minimal exposure group, transport-based SB significantly decreased over time, while transport-based MVPA increased over time. These changes corresponded with a decrease of 13.36 minutes of transport-based SB (t=-2.510, p=.014) and an increase of 5.04 minutes of transport-based MVPA (t=2.072, p=.042). For the no exposure group, an inverse trend was visible: the total percentage SB increased significantly, while total LPA and transport-based LPA decreased over time (Table 2). In absolute terms, total LPA decreased with 28 minutes per day (t=-5.777, p<.001).

Table 2. Mean total and transport-based physical activity levels

		T0	T2	t, p
Maximal exposure	% SB	64.17 (7.86)	64.44 (8.54)	0.42, 0.679
	% LPA	31.79 (7.65)	31.57 (7.86)	-0.32, 0.749
	% MVPA	4.03 (2.66)	3.99 (2.74)	-0.19, 0.85
	% transport-based SB	50.44 (13.86)	47.63 (13.28)	-1.87, 0.065
	% transport-based LPA	34.04 (10.02)	34.57 (11.38)	0.41, 0.679
	% transport-based MVPA	15.51 (11.91)	17.80 (12.89)	1.72, 0.088
Minimal exposure	% SB	65.04 (8.70)	65.90 (10.06)	1.03, 0.305
	% LPA	31.12 (8.32)	30.17 (9.58)	-1.19, 0.237
	% MVPA	3.85 (2.79)	3.93 (2.97)	0.26, 0.795
	% transport-based SB	**51.37 (13.35)**	**47.77 (13.14)**	**-2.13, 0.037**
	% transport-based LPA	35.04 (12.22)	35.37 (12.12)	0.21, 0.836
	% transport-based MVPA	**13.57 (11.44)**	**16.86 (13.13)**	**2.34, 0.022**
No exposure	% SB	**64.81 (6.10)**	**67.01 (7.58)**	**2.21, 0.031**
	% LPA	**31.46 (5.99)**	**29.10 (7.19)**	**-2.49, 0.016**
	% MVPA	3.73 (2.21)	3.89 (3.08)	0.40, 0.689
	% transport-based SB	46.68 (14.85)	50.16 (15.48)	1.54, 0.128
	% transport-based LPA	**35.57 (12.00)**	**31.18 (11.76)**	**-2.44, 0.018**
	% transport-based MVPA	17.74 (13.87)	18.67 (15.48)	0.40, 0.691

Intervention effects on transport-based and total physical activity levels

The interactions between time x exposure group were examined to explore whether changes over time were different for the three exposure groups. Significant interaction effects were found for both the minimal exposure and maximal exposure group, indicating that changes over time were significantly different for the no exposure group. In both exposure groups, the percentage transport-based SB was significantly lower and the percentage transport-based LPA was significantly higher compared to the no exposure

group (Table 3). The significant interaction terms for transport-based SB and transport-based LPA are visualized in figures 2a and 2b.

Table 3. Intervention effect for exposure groups and users, on total and transport-based physical activity levels.

Adjusted model (age, gender, educational level, employment, car ownership)				
	T2 vs. T0			
	Maximal vs. No exposure		Minimal vs. No exposure	
Total PA	*B (95% CI)*	*p*	*B (95% CI)*	*p*
% SB	-1.91 (-4.20; 0.38)	.102	-1.63 (-4.05; 0.80)	.188
% LPA	1.90 (-0.38; 4.18)	.103	1.68 (-0.73; 4.10)	.171
% MVPA	-0.03 (-0.93; 0.87)	.950	-0.08 (-1.03; 0.87)	.865
Transport-based PA				
% SB	**-6.25 (-11.38; -1.13)**	**.017**	**-7.52 (-12.92; -2.12)**	**.007**
% LPA	**4.92 (0.54; 9.30)**	**.028**	**4.77 (0.15; 9.38)**	**.043**
% MVPA	1.36 (-3.30; 6.02)	.566	2.81 (-2.09; 7.72)	.260

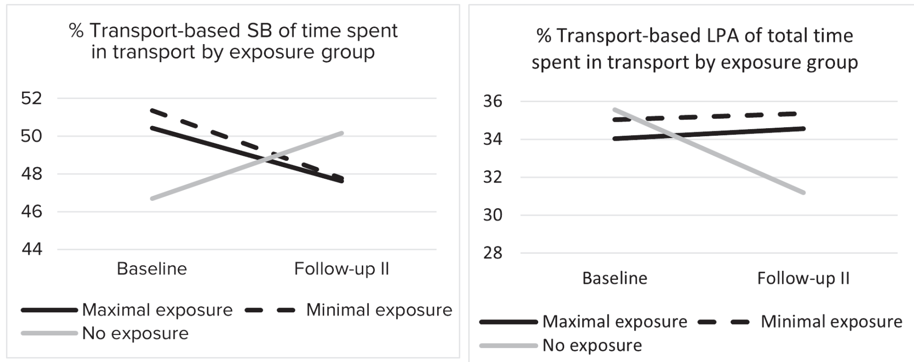

Figure 2a-b. Visualization of significant interaction terms between exposure group and transport-based PA levels.

Health-related quality of life, social activities and meaningfulness

In all three groups, the trend of the total score for health-related quality of life was negative, implying a decline of well-being, but no significant changes were found for the maximal and no exposure groups (Table 4). For the minimal exposure group, the total score on the health-related quality of life decreased significantly between T0 and T2 (t=-2.09, p=.039).The score for social activities at baseline was significantly lower in the maximal exposure group, compared to the no exposure group. Albeit not significant, the trends for social activities and meaningfulness were positive for the maximal exposure group and negative for the minimal and no exposure group. One-way ANOVA analyses showed no between-group differences at T2.

Table 4. Changes in health-related quality of life, social activities and meaningfulness

	T0	T2	t, *p* (T2-T0)
Maximal exposure (N=105)			
Health-related quality of life	0.94 (0.11)	0.89 (0.18)	-1.72, 0.089
Social activities	5.80 (1.97)*	5.91 (1.83)	0.71, 0.479
Meaningfulness	12.07 (2.22)	12.24 (2.02)	0.82, 0.416
Minimal exposure (N=80)			
Health-related quality of life	0.93 (0.11)	0.91 (0.11)	**-2.09, 0.039**
Social activities	6.05 (1.67)	5.94 (1.66)	-0.60, 0.548
Meaningfulness	12.21 (1.69)	11.86 (1.81)	-1.76, 0.082
No exposure (N=56)			
Health-related quality of life	0.93 (0.13)	0.89 (0.14)	-1.75, 0.084
Social activities	6.49 (1.73)	6.19 (1.78)	-1.55, 0.125
Meaningfulness	12.30 (1.52)	11.97 (1.56)	-1.67, 0.100

*= score significantly different from the no exposure group

Intervention effect on health-related quality of life, social activities and meaningfulness

Beta's of the interactions between time x exposure group showed an increase of the score on social activities and meaningfulness in the maximal exposure group compared to the no exposure group, while this was not the case in the minimal exposure group. However, these interactions were not statistical significant (Table 5).

Table 5. Intervention effect for exposure groups, on health-related quality of life, social activities and meaningfulness

	T2 vs. T0			
	Maximal vs. No exposure		Minimal vs. No exposure	
	B (95% CI)	*p*	*B (95% CI)*	*p*
Health-related quality of life	.004 (-.04, .049)	.862	.006 (-0.04, 0.05)	.793
Social activities	0.45 (-0.09, 0.99)	.101	0.27 (-0.30, 0.83)	.352
Meaningfulness	0.44 (-0.14, 1.02)	.134	-0.01 (-0.62, 0.60)	.982

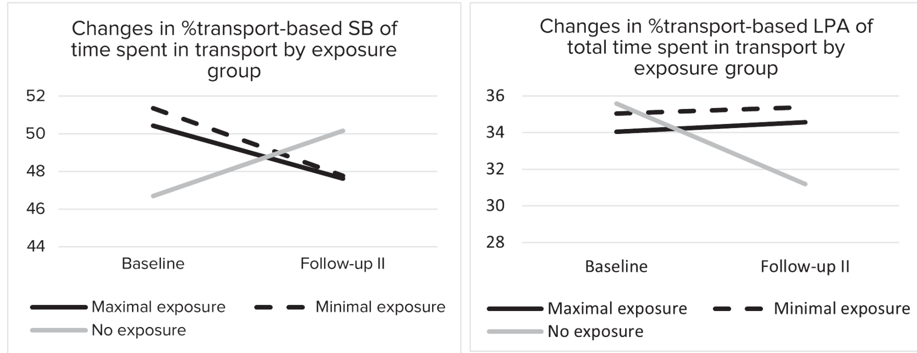

Figure 3a-b. Visualization of significant interaction terms between exposure group and social activities and meaningfulness.

DISCUSSION

Main findings

The aim of this study was to assess the effects of a major urban redesign project, on physical activity levels, active transport and health-related quality of life in adults, at 29-39 months after opening of the new infrastructure. Despite the COVID-19 outbreak and lockdown policies during follow-up, both the maximal and minimal exposure groups showed significantly different trends regarding transport-based physical activity levels compared to the no exposure group; In the exposure groups, the trend for transport-based SB was negative, while it was positive for the no exposure group. Also, transport-based LPA remained stable in both exposure groups, while it significantly decreased in the no exposure group. At this point in time, no significant intervention effects were found for total daily physical activity levels. Also, although the health-related quality of life outcomes increased in the maximal exposure group compared to the minimal and no exposure groups, these effects were not statistically significant.

Physical activity and active transport

Previous research showed promising results regarding the effects of infrastructural changes on physical activity and active transport [29, 189]. However, especially in larger infrastructural projects, effects are generally small or non-existing [30]. Large changes in entire systems may lead to changes in physical activity, active transport and sedentary behavior, but also to compensatory adaptive processes and feedback loops that make it harder to assess clear mechanistic pathways and direct effects [89]. The current study confirms that changes in the entire urban infrastructure might take more time to evoke larger effects on health behaviors. The short-term evaluation of this project found favorable intervention effects on transport-based sedentary behavior [219], but the effect sizes were relatively small. The current study revealed that these trends were sustained over time, and effect sizes almost doubled at the second follow-up. This confirms that rigorous changes in the built environment can lead to sustainable behavioral change, but changes take more time to occur and to be measurable [242]. Therefore, it is important to ensure long term follow-ups when evaluating large-scale built environmental interventions, to explore the full potential of the newly designed areas.

The recommendations of recent systematic reviews and research to prolong follow-up times turned out to be valid, but also has some challenges. In research in general, drop-outs are a threat to research designs and various strategies are followed to prevent loss to follow-up. In studies in which place matters, loss to follow-up is not only a result of the loss of interest of participants, but also a result of people that are moving. Especially in lower socioeconomic status neighborhoods where participation is lower, more people live in social housing, which is known for a quicker turnover of residents [246]. Also, specific populations such as students are moving more often. This could also be the explanation for the finding that drop-outs between baseline and follow-up were younger and less often a car owners. Also, the COVID-19 contact restricting measures could have caused additional drop-outs, especially for more vulnerable individuals. Future research should investigate how measurement methods, incentives and other measures can improve the retention of individuals in longer-term evaluations.

Not only the relative amount of transport-based physical activity decreased, but the absolute amount of transport-based sedentary behavior decreased as well. In the maximum and minimum exposure groups transport-based sedentary behavior decreased with 11 and 13 minutes per day, respectively. In addition, trends of transport-based light physical activity were significantly different for the exposure groups compared to the no exposure groups, as transport-based LPA decreased over time for the no exposure group while it remained stable for both exposure groups. Previous research found that in some contexts, active transport accounted for 31% of the total energy expenditure and for 13% of the sedentary time during 7 measurement days [247]. But despite the changes in transport-based physical activity levels, we found no changes on the total physical activity levels. Possibly, the effects on transport-based physical activity are still too small to result in changes in the total physical activity levels. This could be due to the small scale of Dutch cities, which make trip distances in the Netherlands are rather short, which in turn minimizes the effects of active transport trips on the total amount of physical activity. Also, it is possible that the increase in transport-based physical activity is compensated by less physical activity in other domains [229].

Remarkably, the changes in transport-based physical activity were comparable for the minimal and maximal exposure group, with a slightly larger effect for the minimal exposure group. This could be explained by the improved connectivity in the maximal exposure group after the tunneling of the highway. While previously, only a few intersections were available for pedestrians and cyclists, it is now possible to cross the Green Carpet at various points. Trips can now be more efficient and thus shorter. However, an in-depth trip-analysis is necessary to further investigate this argument. Further, for the minimal exposure group, the Green Carpet might act as a new destination or attractive route for active transportation. Also, in the six years between baseline and follow-up, some smaller investments in the built environment of the minimal exposure group were made, such as a new 'slow traffic' route, which aimed to improve the livability and creating greater connectivity in the residential area of this group. This might have caused a shift regarding walking and bicycling for transportation.

Health-related quality of life, social activities and meaningfulness

Both social activities and meaningfulness showed a positive trend over time for the maximal exposure group, while these were negative for the minimal and no exposure group. Although these differences were not statistically significant, the maximal exposure group is following a different trend after the opening of the Green Carpet. The lack of statistical significance might be caused by the relatively small sample size. The positive trend in social activities and meaningfulness for the maximal exposure group acknowledges previous research that found associations between social well-being and increased city density, the presence of facilities such as bars and restaurants, and distance to the city center [248]. Also, our results are in line with previous research that found that green space in the living environment is related to social factors such as people's feeling of loneliness [249].

The score on health-related quality of life showed a slightly negative trend over time for all groups. The negative trend of the health-related quality of life score might accelerate as age increases, as the minimal exposure group was significantly older and showed a significant decline in health-related quality of life score over time. In an evaluation of a major infrastructural intervention in Belfast, health-related quality of life scores also followed a negative trend, with significant decrease over time [250]. However, this study found a significantly smaller decline in the intervention group [250]. Furthermore, the second follow-up took place during the COVID-19 pandemic. Previous research showed that the pandemic and its restrictions in movement and social contacts had a negative impact on quality of life [251, 252], which could explain the decline in health-related quality of life as well.

According to socioecological models, health and wellbeing are influenced by proximate factors at the micro/interpersonal level such as health behaviors [111]. This means that changes in the built environment should change proximate factors such as infrastructural stressors (e.g. environmental conditions and safety), health behaviors or social participation to affect general health and well-being. Therefore, it might even take more time before effects in health and wellbeing are present and measurable. To improve overall health and wellbeing, or to prevent further declines, larger changes in proximate factors such as the total amount of physical activity might be necessary.

Strengths and limitations

A limitation of this study was the inability of the design to control contextual factors. The follow-up measurement took place between September 2020 and July 2021, which was in the middle of the COVID-19 pandemic. During this period, several contact limiting measures were in place to reduce the spread of the virus. Also, all inhabitants of the Netherlands were encouraged to work from home as much as possible, which has affected the amount of commuting. At the time of the total lockdown and curfew (between the 18th of December 2020 and 1st of April 2021), the measurements were paused to comply with COVID-19 regulations and to limit the effects of the measures on the results of this study. However, while it is impossible to quantify the effects of the preventive measures on all outcomes, it is very likely that the pandemic has had some effects on the results. As all COVID-19 measures were implemented country-wide, the effects are expected to be similar in the exposure and no exposure groups which may cancel out the influence of these measures when investigating the trends over time between the exposure and no exposure groups.

Apart from the COVID-19 pandemic, other contextual factors might have influenced the outcomes during the six years between baseline and follow-up, as the Green Carpet is not a stand-alone intervention. The Green Carpet project changed the connectivity, amount of traffic an aesthetics of the affected neighborhoods. But there also might be a change in the social environment of these neighborhoods that comes along with new infrastructure, new dwellings and new inhabitants [253]. Possible gentrification and psychological displacement of the individuals that remained living in the study area can also have an effect on the mental health status of these individuals [254]. Qualitative research is needed to further investigate the effects contextual factors and the social environment on the results of this evaluation. Further, the sample size of this longitudinal analysis was relatively small, as the dropout rate increased over time. Finally, 38% of the participants at baseline provided valid data at baseline and follow-up. As a result, some of the non-significant findings might be due to a lack of power. Lastly, when interpreting

the results of this study, one should take into account that the study sample was higher educated and older compared to the general Dutch adult population [255, 256].

CONCLUSION

This study identified significant intervention effects of a major urban redesign project on transport-based physical activity levels at 29-39 months after opening of the newly designed area. The results showed significant intervention effects on transport-based sedentary behavior and transport-based light intensity physical activity for both exposure groups, compared to the no exposure group. In comparison to the shorter-term evaluation and despite the COVID-19 physical isolation policies, the effect sizes increased over time. These results emphasize the potential of the built environment in changing and sustaining healthy behavior over a longer period of time. Scores on social activities and meaningfulness increased in the maximal exposure group while it decreased in the minimal and no exposure groups, but changes over time were not statistically significant. As the intervention area is still under construction, even longer follow-up terms might be needed to explore its full potential.

CHAPTER 9

General discussion

The main aim of this thesis was to evaluate the effects of a major infrastructural intervention on physical activity, sedentary behavior and health-related quality of life. In this chapter, the main findings of the systematic review, effect- and process evaluation are summarized. The main findings are followed by theoretical and methodological considerations, the discussion of relevant contextual factors, and finishes with recommendations for research and practice.

MAIN FINDINGS

Systematic review

Chapter 2 describes the systematic review of the available literature on the effect of built environment infrastructural changes (BEICs) on physical activity, active transport and sedentary behavior. The results showed that BEICs can lead to changes in overall physical activity and active transport, especially with regard to bicycling. Remarkably, none of the available articles assessed effects on sedentary behavior. The effectiveness of the interventions varied greatly across intervention types and types of outcome measures. In general, studies specifically targeting physical activity and smaller interventions showed more effects than those addressing more global and drastic infrastructural changes. Several factors might have affected these results. The more drastic infrastructural changes imply major changes to whole systems [49]. This type of intervention may eventually lead to changes in physical activity, active transport and sedentary behavior, but also to compensatory adaptive processes and feedback loops that make it harder to identify clear mechanistic pathways and direct effects [89]. Changes in behavior might therefore happen on a longer term, so might not be picked up with relatively short term studies. Also, the risk of outcome measurement bias and bias in the selection of reported results was higher in the studies that evaluated smaller on- and off-road walking and/or bicycling trails in comparison to the more extensive infrastructural interventions. So, studies with a higher risk of bias were more likely to report significant changes in outcomes than studies with a lower risk of bias. Applying more refined and complex study designs seems to decrease the possibility to detect significant changes in physical activity and active transport. To improve the understanding of the potential of BEICs to increase physical activity and active transport and decrease sedentary behavior, the quality of research should be improved. Possible improvements are the use of device-based context-specific measurements to assess sedentary behavior, physical activity and active transport, the inclusion of multiple groups based on proximity to the intervention, the assessment of individual-level exposure and proximity to the intervention and the provision of detailed description of the context in which an intervention takes place.

The role of context in research and practice

Chapter 3 describes how the context of mid- and long-term urban reconstructions such as the Green Carpet influences design and implementation conditions that prove crucial to project achievement. The socioeconomic and geographical context were especially of importance during the agenda setting phase. The geographical context influenced the planning procedure due to the physical location of the city, which is bordered by protected natural areas. The poor socioeconomic position of neighborhoods bordering the Green Carpet stressed the need for change in this area. The formal procedures during the planning phase of the project were carried out within the stated legal frameworks, and thereby the legal context shaped the project. The political context evoked most of the changes during the planning and implementation phases, due to the political agency (e.g. by way of advocacy or lobbying) of specific stakeholders, national policies, and obligatory and voluntary consultations of the inhabitants and stakeholders. The changes in the context influenced the design and implementation conditions that prove crucial to project achievement. For example, a “Gentlemen’s Agreement” that was concluded between public parties in the A2 Maastricht Project Agency and the A2 Neighborhood Platform resulted in practical changes in the project such as the realization of noise barriers, and a greater support for the project among the A2 Neighborhoods Platform. Due to the constant interactions between context and the project, health impacts can hardly be exclusively ascribed to the initial project. Traditional evaluation designs often ignore these process dynamics in order to maintain ‘design fidelity’. To improve the internal validity, interpretation and implications of future evaluations, we recommend adopting a complex systems approach and mixed methods design that enables investigating contextual dynamics and project adaptations over time.

Associations between perceived neighborhood walkability and physical activity

The results of the baseline measurements of the effect evaluation showed that more physical activity-supportive environments such as the presence of places to go within walking distance and the presence of attractive buildings are associated with less sedentary behavior and an increase in moderate-to-vigorous physical activity, but might not affect light physical activity (chapter 4). However, the potential of the built environment to affect physical activity levels differed for more and less advantaged individuals in society (i.e. lower educated individuals and higher educated individuals). For less advantaged individuals, the absence of (physical) barriers (i.e. highways, railways, traffic) might lead to more physical activity and less sedentary behavior. For more advantaged individuals, the presence of physical activity supporting elements (i.e. aesthetics, presence of destinations) was found to be associated with more physical activity. Further, context-specific analyses of the data showed that associations between perceived neighborhood walkability and neighborhood-based physical activity depends on the time that is spent in the home neighborhood (chapter 5). Perceived neighborhood walkability only affected neighborhood-based physical activity levels for those who spent relatively more time in their home neighborhoods. Physical activity facilitating features in the home neighborhood were only associated with more neighborhood-based physical activity for more advantaged individuals. These findings imply that the same physical environment might have different effects on more and less vulnerable individuals.

Effectiveness

To evaluate the effects of the Green Carpet on physical activity, sedentary behavior and active transport, two follow-up measurements after the opening of the Green Carpet were executed. At the first follow-up, about 3-15 months after the official opening of the Green Carpet, no increases in total or transport-based physical activity were found for the minimal and maximal exposure groups in Maastricht. However, a decrease in transport-based MVPA and increase in transport-based SB was observed in the no exposure group. This might be an indication that the Green Carpet prevents the increase in transport-based SB over time. Subgroup analyses showed that the area-based differences might reflect the differences between users and non-users, but this should be interpreted with caution, due to potential selective mobility bias.

Although there were no detectable changes in the total amount of physical activity at the population level in the short term, spatial analyses showed that the changes in the environment still changed the physical activity patterns of the residents that lived in adjacent neighborhoods. Both lower and higher educated individuals tended to use the new infrastructure at the first follow-up (Chapter 7). This might indicate a rerouting of pre-existing travel, or an actual shift in physical activity behavior that will eventually lead to increases in the volume of total daily physical activity, as a result of prolonged favorable physical activities such as active transport. These results show 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. 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, particularly to improve our insights in creating impact for vulnerable populations.

In agreement with the short-term follow-up, the longer-term follow-up at 29-39 months after opening of the Green Carpet showed significantly different trends regarding

transport-based physical activity levels for the minimal and maximal exposure groups, compared to the no exposure groups. In the exposure groups, transport-based sedentary behavior decreased over time, while it remained stable in the no exposure group. The estimates of this interaction between exposure group and time almost doubled between follow-up I and follow-up II. In absolute terms, the amount of transport-based sedentary behavior decreased between baseline and longer-term follow-up with about 10 minutes per day in both exposure groups. Also, transport-based light intensity physical activity remained stable in the exposure groups, while it significantly decreased in the no exposure group. No significant intervention effects were found for total physical activity levels nor for health-related quality of life outcomes. The trends for social activities and meaningfulness were positive for the maximal exposure groups, while they were negative for the minimal and no exposure groups.

The role of social factors in the relationship between environment and behavior

The results of the quantitative effect evaluation evoked some unexpected findings regarding the relationship between environment and behavior that could not be explained by the results of the effect evaluation itself nor by evaluation of the context. One of these findings was the observation in the hot spot analyses that one of the neighborhoods bordering the Green Carpet, Wyckerpoort-Noord, took hardly any advantage of the newly designed area. No physical activity hot spots were present in this neighborhood at follow-up, but there were limited logical explanations for this in our effect and context evaluation studies. From previous research, it is known that many less tangible and measurable constructs, such as social cohesion, social safety and sense of community can affect the physical activity levels and health status of inhabitants of neighborhoods [257-259]. However, these elements of the social environment are difficult to quantify using traditional evaluation methods. Therefore, one of the recommendations of previous research was to use ethnographic methods to observe tacit mechanisms and to give the affected residents the chance to think about their experiences, or to let them rationalize their thoughts [86, 260]. To investigate the possible effects of these intangible social constructs on the relationship between environment and behavior in Wyckerpoort-Noord, an architect duo called Dear Hunter was commissioned to perform ethnographic research in the Green Carpet area. Ethnography "puts something into words that, prior to this writing, did not exist in language" [261]. In this type of research, description plays an important role, as it does not require the ability of subjects to put into words their thoughts, reasoning and motives. This is especially important because a lot of aspects in the social environment are 'silent'. For example, things might be pre-linguistic, i.e. it concerns implicit knowledge or skills that individuals cannot simply put into words. Also, the distribution of power within a community, cultural norms, or the complexity of an issue might affect people's ability to express themselves. The methods of the ethnographic research by Dear Hunter is presented in panel 1. The results are presented in a report consisting of four maps explaining the relationship between social and physical elements of the environment.

Panel 1. Ethnographic research Dear Hunter

Ethnographic research
In a collaboration with Dear Hunter, an ethnographical perspective was added to the current project to further understand and interpret the findings of our quantitative evaluation by investigating intangible social factors. Dear Hunter is an architect duo that uses 'cartopology' to connect physical places and everyday life using maps (www.dearhunter.eu). Cartopology is a combination of anthropology and cartography. In cartopology, anthropology adds social meaning to traditional maps of a physical environment. This is done through zooming in on specific environmental elements that take on a specific meaning in the everyday lives of inhabitants of the research area. To create those maps, Dear Hunter preferably lives or spends a certain amount of time in the specific location to experience and observe the daily life, and to talk to the inhabitants of the prespecified area. For the current project, Dear Hunter spent a few days in the Green Carpet area. This resulted in four maps, all visualizing a different part of the Green Carpet (www.dearhunter.eu/indigo). They indicated that in the southern (and higher SES) part of the Green Carpet, the newly designed area already blended into the existing surrounding neighborhoods, while in the northern part of the Green Carpet, the new infrastructure seems to have limited connections and effects on the adjacent neighborhoods. One of the neighborhoods that doesn't seem to take advantage of the new area is Wyckerpoort-Noord. This neighborhood has a low socioeconomic status and it consists mainly of social housing. Interestingly, the backyards of some houses in this neighborhood are bordering the backyards of the newly built houses at the Green Carpet, but interactions between the two are lacking. Lastly, the Green Carpet is perceived as a new social boundary, which is physically reinforced with a concrete wall between the old social houses in Wyckerpoort-Noord and the new expensive houses of higher-income residents at the Green Carpet.

In October 2021, we organized a residents meeting to discuss the results of our quantitative studies and the findings of Dear Hunter. Some of the major points of discussion during the meeting were the missing connections between the neighborhood and the Green Carpet, but also the lack of liveliness in the neighborhood. The inhabitants explained that the lack of connection and the lack of liveliness is a result of various factors. For example, there is a lack of physical destinations (i.e. shops, pick-up points for packages, cafés) that can facilitate spontaneous meetings. Also, the constant turnover of inhabitants prevent investments of inhabitants in their social or physical environment (i.e. contact with neighbors or maintaining the front yard). In addition, the concrete wall between the new houses at the Green Carpet and the existing houses in Wyckerpoort-Noord created in a feeling of inferiority among the inhabitants of the existing houses. This feeling was reinforced by a lack of communication between the contractor and inhabitants about the constructions in their living area.

Theoretical considerations

This thesis started with the introduction of socioecological models that are used to explain the effect of the environment on behavior and health. More general models proposed that different levels of influence affect health and health behavior [12, 21], while the EnRG framework specifically described a dual-process approach[20]. This paragraph discusses the results of the studies in this thesis in light of these theoretical frameworks.

Socio-ecological perspective

Based on socio-ecological models, we stated that changes in the environment are able to change health behaviors of the entire population. Already in 1985, Rose argued that changes to the environment can be seen as a population strategy of prevention; they work through rigorous changes in the entire system and affect all individuals [262]. Over the course of years, other researchers argued that Rose's approach does not address the underlying mechanisms that lead to different distributions of risk exposure between socially defined groups within populations [263]. They argue that structural approaches might thereby increase health inequalities and population level approaches should be complemented with interventions that address the needs of vulnerable populations [263]. However, this argument was questioned by other researchers, who stated that population prevention does not necessarily worsen health inequalities, but that this depends on the prevention strategy [264]. Despite of this ongoing debate, the effect of socioeconomic inequalities in the relationship between environment and behavior are currently rarely studied, so evidence is lacking [15]. Therefore, we examined socioeconomic differences in the associations between perceptions of the environment and physical activity levels. These analyses showed that the associations between the perceptions of the environment and behavior are different for more vulnerable individuals (e.g. lower educational level or higher BMI) compared to less vulnerable individuals (e.g. higher educated, no health-related problems). In the light of socio-economic health inequalities, this confirms that structural prevention strategies might not have the same impact on all inhabitants of the affected area. We found that the presence of barriers for physical activity was associated with more sedentary behavior for more vulnerable individuals, while this was not the case for less vulnerable individuals. On the other hand, facilitating features in the environment such as the presence of facilities and aesthetics were associated with more physical activity for the less vulnerable individuals. These findings are in line with the theory behind the Hierarchy of Walking Needs [142], which describes that the lower layers of the hierarchy (feasibility, accessibility and safety) should be fulfilled before the higher order layers (comfort and pleasurably) become important when people decide to walk or not to walk. For more vulnerable individuals, the lower order layers that are related to barriers in the environment are relevant while for less vulnerable individuals higher order layers, related to facilitators of physical activity, are more determining.

Although different subgroups in society have different needs regarding barriers and facilitators of physical activity, this does not mean that it is impossible to serve different groups at the same time and improve population-wide physical activity levels. The Green Carpet project included environmental changes on various layers of the hierarchy of walking needs; safety from traffic, comfort, aesthetics and the access to facilities. Analyses showed that this integrative approach resulted in equal use of the Green Carpet by different subgroups [265]. Also, it showed that the use of the Green Carpet was significantly associated with less transport-based sedentary behavior and more transport-based moderate-to-vigorous physical activity, but only for lower educated individuals. However, we also found that at least one neighborhood did not benefit from the newly designed area. This could be explained by the conceptual framework of Panter et al. (2017), in which they expressed that environmental and policy interventions are socially embedded and operate within a larger system. Hereby, the social environment plays an equally important role in the relationship between environment and behavior. In the current study, interactions between the physical and social environment were identified by the ethnographic research of Dear Hunter and the discussion of our research results during the residents meeting. According to the ethnographic research and the explanations of the residents, several social factors influenced the relationship between the physical environment and behavior. For example, a concrete wall between the existing houses in Wyckerpoort-Noord and the new houses at the Green Carpet was found to reinforce the social barrier between the "poorer" inhabitants of the social houses and the "richer" inhabitants of the new houses at the Green Carpet. The wall created a feeling of inferiority among the inhabitants of the social houses, since they had not been informed and did not have any say in selecting an appropriate solution to the 2 meter surface elevation above the old neighborhood surface. As a consequence, this new social barrier between old and new houses in the Green Carpet area is a risk for gentrification. Gentrification has several definitions, but is generally defined as a process in which under-resourced neighborhoods are physically upgraded, which causes an import and replacement of former residents by new higher socio-economic status residents [266]. In some cases, this leads to increases in housing prices, which contributes to the physical displacement of low-income residents who cannot longer afford to live in the specific neighborhood [267]. However, displacement can also be psychologically, when inhabitants feel as if they feel excluded from the new social and cultural identity of the new area [268]. Although physical displacement is not (yet) the case in Wyckerpoort-Noord, the residents meeting revealed indications for psychological displacement, which can lead to loss in social capital and social networks, and eventually affect the health status of the individuals living in these neighborhoods [254].

Also, the inhabitants mentioned a quick turnover of neighbors, which is a well-known phenomenon in neighborhoods with social housing [246]. This phenomenon affects the investments people do in their social and physical environment. Previous research established that social interactions mediate the relationship between the built environment and 'place attachment' [269], which is the emotional bond between an individual and a specific place [270]. A sufficient place attachment and a pleasant social environment in the home neighborhood is important as it is associated with well-being, especially in older adults and more vulnerable individuals [271, 272]. However, the relationship between public spaces and the facilitation of social encounters is complex, as changes in the built environment do not guarantee changes in sense of community, social interactions or social cohesion [273]. In a recent article, Bussemakers et al. (2022) present three points on which governments and policymakers can act to bring policy visions regarding meeting places in the public open space into practice. One of them being that policymakers should increase the trust in the community that they want to engage in the processes. They argue that citizens should not only be involved in formal consultations, but they should be able to make decisions and should have executive power [274]. This would facilitate the process to create ownership over the public space and take responsibility for the own neighborhood [274]. However, currently there are no strict rules for citizen engagement and co-decision-making other than legally obligatory consultations.

Participation is one of the pillars of the new Environment and Planning act of the Netherlands, which is planned to be implemented in 2023. An evaluation of 300 built environmental projects that already started to experiment with various forms of citizen- and stakeholder participation found that dialogue between the initiators of the projects and involved inhabitants, companies and social organizations, had added value and led to more quality and support, and more acceleration of processes due to less legal procedures [275]. Although citizen participation can add valuable insights into environmental- or real estate projects, it remains a difficult process as the motives for participation in such projects are different for government, citizens and executive parties [276]. According to Verheul et al., in real estate projects, the motives of the developers are generally to increase the support from the local government or politics, avoiding lengthy lawsuits or legal procedures, and to create a better reputation in the media. This was also the case in Maastricht, where stakeholders and inhabitants were consulted via various ways. Consultations did not lead to significant changes to the project, but there were also hardly any legal objections to the plans (Chapter 3). When it comes to participatory processes, Verheul et al. describe various types of participants and non-participants [276]. Some of them are satisfied with just being informed, while others want an active role during the entire process. Especially in vulnerable neighborhoods that could benefit from citizen participation, there are many non-participators. Among non-participators, there are individuals who are not interested and individuals who refuse to participate because they feel that they thereby implicitly consent to the plans. Besides them, there is a group of 'dropped out' individuals and a group 'survivors'. The drop outs have little trust in society, government and other people, and/or experience cultural or language barriers. The group survivors is trying to make ends meet and usually a participation process is not their priority. Those last two groups might be overrepresented in vulnerable neighborhoods and often only the *usual suspects* are participating. These usual suspects have the time and skills to engage in participation processes, but are not representative of all inhabitants of the affected area. During the resident meeting in Maastricht, inhabitants indeed acknowledged that many of the inhabitants of this neighborhood feel like they are in survival mode; their health and living environment are not their first priority. Though, taking part in participation processes could improve their sense of purpose and wellbeing [277]. Although participation might contribute to an increased livability of neighborhoods and improved health and wellbeing of inhabitants, the question remains how governments and contracting parties can shape participatory projects in such a manner that it is satisfactory for all parties to participate. Also, when organizing participatory processes, one should think about recruitment strategies in order to involve former non-participators as well.

The studies in this dissertation acknowledge the direct and indirect relationships between environment and health(behaviors) as explained by socio-ecological models. Also, the current research verifies that personal characteristics can moderate the indirect effects of the environment on behavior. Our qualitative explorations have given insights in the less tangible social factors that seem to interact with elements of the physical environment. Therefore, theoretical frameworks and future research should put more emphasis on the role of the social environment and citizen participation when investigating the effects of the physical environment on behavior and health.

A complex systems approach

The socio-ecological models presented in this thesis described the effects of the environment on health and health behaviors through various layers of influence, from the personal level to the environmental level [12, 17]. It is known that environmental influences are highly complex as they vary over space and time, and the individuals exposed to the environment also travel through space and time [278]. Previous research acknowledged that complex problems require a systems approach that accounts for the complexity of the real world [279]. In complex adaptive systems, it is assumed that the interaction between parts of the system are non-linear, meaning that changes in one part of the system may lead to small or large changes in other parts. Also, it can lead to different outcomes over time [280]. In this dissertation, a range of research designs were

combined to account for the complex nature of the relationship between environment and behavior. A quantitative research approach was used to assess the relationship between (perceptions of) the environment and physical activity, active transport and health-related quality of life. Qualitative approaches were applied to describe the context in which the Green Carpet project was created and evaluated. In addition, ethnographic place-based research was commissioned to better understand the intangible social factors and finally, a residents meeting was organized to get feedback from inhabitants about the results of the quantitative and ethnographic research. It is known that a mixed methods design will result in a more thorough understanding of the complexity of the system and enables to account for the dynamic reality [281]. A recently published systematic review found that the use of systems approaches to increase physical activity levels is still at an early stage of development, and acknowledges that the field requires greater application of mixed-methods evaluation approaches [282]. The ENCOMPASS framework might help researchers in the future to apply a complex adaptive systems approach in all stages of evaluation research [283].

Methodological considerations

The results of the studies presented in this dissertation should be considered in light of their strengths and limitations. The methodological considerations discussed in the paragraphs below concern the design of the experiment including discussion about natural experiments in general, measurement and analyses methods and follow-up time. These paragraphs are followed by a discussion about the definition of the home neighborhood, and the use of subjective vs. objective measures of the neighborhood environment.

Design of experiment

Natural experiments

Natural experiments provide the opportunity to investigate projects, policies or events in a real-world setting [39]. This offers unique research opportunities, but some limitations should be considered. Most important, in natural experiments researchers have no control over external factors that impact on the intervention and outcomes. Half way during the current project, the COVID-19 pandemic started. During the second follow-up measurement, several contact-limiting rules were in act to stop the spread of the virus. Although this impacted both on the intervention and control groups, it is unclear what effect this had on the actual outcomes of the study. Another limitation of the design is that the neighborhoods that were selected to recruit the participants of the control group were chosen based on the properties and sociodemographic characteristics of the neighborhood. Yet, it is impossible to find neighborhoods in a different city that have the exact same set-up and demographic profile.

Even though reviewers are often critical about natural experiments due to these type of methodological differences with for example randomized controlled trials, they lead to much needed evidence regarding population-level strategies to improve behavior and health [284].

Measurement and analyses

The current experiment assessed physical activity levels, but also the amount of sedentary behavior. Both in our cross-sectional analyses and in the effect evaluations, sedentary behavior turned out to be an outcome measure of significance. In the past, several cross-sectional studies investigated the associations between neighborhood walkability and the amount of sedentary behavior [285-287], but results were inconsistent and longitudinal evidence was lacking. Therefore, this experiment is one of the first longitudinal study that showed the effects of the built environment in decreasing the amount of sedentary behavior, especially sedentary behavior during transport. This indicates that the environment does facilitate the substitution of passive forms of transport by more active forms, such as walking and cycling.

We used device-based measurements to assess context-specific physical activity levels, active transport and sedentary behavior. The use of these type of measurements allowed different types of analyses on the data. The analyses of the baseline data showed the importance of the incorporation of context in studies that evaluate the effect between environment and behavior. For example, associations were found between perceptions of the home neighborhood and physical activity and active transport, but context-specific analyses showed that this was mainly for individuals that spent more time in this specific environment. Also, the incorporation of both activity and location data enabled visual analyses, such as Hot Spot Analyses [265]. Although Hot Spot analyses are not frequently used in behavioral science, they give important insights in the use of areas of interest. Hereby, we were able to show that after the opening the new infrastructure of the Green Carpet, physical activity hot spots moved from adjacent streets to the Green Carpet, even though this use did not lead to changes in the total amount of physical activity. Also, it revealed new hotspots, indicating new routes connections between the east and the west of the Green Carpet. It should be mentioned that the use of device-based measurements has challenges as well. Cut off points and algorithms are used to classify activity into intensity levels and types of transportation, and although the same reference values are used at all measurement points and among all studies in this thesis, these values stay arbitrary [288]. In addition, cut off points for activity monitors are established in laboratory settings, while they are applied in a free-living environment [165].

Follow-up time

Another drawback of existing evidence turned out to be the relative short follow-up terms in experiments. Several systematic reviews acknowledged that longer-term studies are warranted [15], as studies with less than 12 months of follow-up may not provide enough time for the inhabitants of the affected area to change their behavior [29]. Although longer follow-up times are recommended, several pragmatic factors make this difficult, such as delays in implementing the intervention loss to follow-up, and the duration of research projects [31]. The follow-up time in the current study ranged between 29-39 months after the opening of the Green Carpet, which enabled us to investigate the changes in behavior over a longer period of time compared to existing studies. In the second follow-up measurement, estimates of intervention effects were indeed larger compared to the first follow-up measurement. This underlines the importance of longer follow-up times in large infrastructural projects. It should be mentioned that although the Green Carpet was opened for a few years, the construction of houses and commercial spaces in the newly designed area was still ongoing during the second follow-up. The redesign of the area will further continue over the coming years. Changing the environment and thereby changing behavior is not a quick fix, but a process that might take generations to have effect. Therefore, the last follow-up measurement in this experiment is only a snapshot from changes up until now, but probably not the end of behavioral change in the intervention area.

Definitions of the home neighborhood

Another methodological consideration is the definition of the environment that is investigated in studies examining the relationship between environment and behavior. Often, researchers are interested in the home neighborhood (i.e. neighborhood environment), but this environment is defined in different ways. For subjective measures, questionnaires mainly refer to the (home) neighborhood environment as the area that one can go to within a certain amount of minutes walking from the home address. This means that the size and shape of the neighborhood environment depends on both the infrastructure and personal characteristics (e.g. ability to walk, walking speed). For objective measures, various definitions of the neighborhood environment can be used, for example administrative units, point locations, buffered point locations and activity spaces [289-291]. In chapter 5, the home neighborhood was defined by a street network buffer of 1.0 km around the home address of participants. Analyses showed that perceptions of walkability of the home neighborhood and physical activity in the home neighborhood were significantly associated, while this was not the case for physical activity in general. This study was the first to show that perceptions of the home neighborhood were only associated with physical activity in the home neighborhood for those spending relatively more time in the home neighborhood. This indicates that not only the definition of the context in which physical activity takes place matters, but also the amount of time that is spent in this context. Finally, a recent review concluded that there is a need of studies that measure the physical environment objectively with methods that measure the environmental exposure beyond home locations and combine this with multiple levels of the socio-ecological approach [292].

Subjective vs. objective measures for neighborhood walkability

The analyses of baseline data revealed several relationships between the perceived neighborhood walkability and physical activity. The perceived neighborhood walkability was assessed using the Neighborhood Environment Walkability Scale, which is a questionnaire that measures the perceptions of the neighborhood walkability on several assets of the environment, such as access to facilities, aesthetics, infrastructure and safety [176]. However, perceptions of the environment are only one type of measures to assess the walkability of an environment or neighborhood. Other measures can be derived from geographic information systems (GIS), observations, or from government statistics. For example, recently a objectively measured walkability index was developed, specifically for the Dutch context [293]. Different individuals may perceive the same environment differently, indicating a discrepancy between the objective and subjective measures of the environment [294]. Research acknowledges that perceptions of the environment are affected by unobservable psychological processes. Additional analyses on our baseline data showed that objective and subjective measures of the environment have different relationships with physical activity [295]. For example, objectively measured pedestrian infrastructure density was positively associated with moderate-to-vigorous physical activity, while its subjective counterparts (i.e. perceived availability and connectivity of sidewalks, presence of crosswalks and pedestrian signals) were not associated with physical activity. On the other hand, perceptions on the amount of greenspace in the home neighborhood were associated with more physical activity, but the objective measures for the amount of green space in the home neighborhood were not. This discrepancy between objective and subjective measures of the environment is described by other researchers as well [294, 296], and confirms the dual process theories: the relationship between environment and behavior works through different mechanisms for perceptions of the environment and the objective environment [20].

Use of research vs. consumer-based activity monitors

Where most participants had no problem in wearing the GPS-logger and activity monitor during the baseline measurements, some of them experienced the devices user-unfriendly, especially during the last measurement round in 2021. Mainly younger participants experienced the devices as old-fashioned. This might be explained by the new technologies that are available on the consumer market for activity trackers (e.g.

Fitbit and Garmin), which has evolved quickly over the past years. The use of consumer activity trackers might be a solution for both 24-hour measurements and dropouts among younger participants. Most activity trackers are waterproof and have a long battery life, which makes it easier to wear it day and night, and consumer market activity trackers are smaller and generally accepted. The use of research versus consumer based activity trackers is a balance between internal and external validity. The devices that are currently used by most researchers are separate GPS loggers (such as the Qstarz GPS-logger) and activity monitors (such as Actigraph or ActivePAL), of which the data were later merged. These devices are used all around the world and they have a relatively good reliability and validity, making them attractive to use in a research setting. In contrast, the internal validity of consumer activity trackers to correctly detect physical activity and active transport is lower [87]. However, these devices are easier to use in a large group of people, can be worn during the entire day and night and the burden for participants is lower, which makes it more feasible to wear them for a longer period of time [297]. Hereby, a more divers and larger group of people might wear the devices for a longer period of time, which is favorable for the external validity. Future research should further explore how newer devices can be used in a valid manner, to increase both the internal and external validity of context-specific physical activity research.

Recommendations for future research and implications for practice

Based on the studies in this thesis and the discussion of theoretical and methodological considerations, several implications and recommendations for future research and practice are identified. These implications and recommendations for future research are discussed in the paragraphs below, starting with higher-level implications regarding the research paradigm and design, and finishing with practical recommendations.

Recommendation for future research

Future research should acknowledge the complexity of the relationship between environment and behavior, and act on this by taking a systems approach and applying a broad range of research approaches. Quantitative research can give insight on the amplitude of behavioral changes, but qualitative research is necessary to interpret and understand the findings, and to explore the context in which an intervention is implemented. Also, more research on the interaction between the physical and social environment is needed to further explore if and how the social environment creates preconditions for behavioral change. To do so, it is important to use participatory research approaches with inhabitants and/or other relevant stakeholders in the area of interest. As different subgroups in society have different wishes and needs when it comes to healthy living environments, it is important to take this into account.

Several practical recommendations for future research are described in the studies presented in this thesis.

I. Sleep, physical activity and sedentary behavior have a separate effect on health [298-300], but as there is a limit of 24 hours in a day, spending more time doing one of the behaviors means automatically that less time can be spent in the others. The relationship between these behaviors and health outcomes can be investigated in so-called compositional analyses [301, 302]. Future research should explore possibilities of compositional analyses in context-specific physical activity research.
II. Even though follow-up times of at least 12 months were recommended at the start of this project, even longer follow-up times might be necessary to measure the full potential of large infrastructural projects. Future research should investigate possibilities to use even longer follow-up periods to explore the full potential of large projects in the built environment.
III. Both objective and subjective measures of the built environment have a predictive value for physical activity and active transport, and these measures seem to work via different mechanisms. For policymakers and executive parties it is recommended to take both measures into account when designing new public and/or residential areas, or designing large infrastructural projects.
IV. It is important to account for differences between less and more vulnerable individuals in society as the environment can have a different association with behavior for subgroups.

Implications for practice

The current research showed that changes in the built environment can affect the behavior of inhabitants. However, the relationship between the built environment and physical activity is just one of many in the entire system. Due to differences in context, it is difficult to predict to what extent the same intervention will result in comparable changes, when implemented in another region or country. For governments, it is important to acknowledge the complexity of specific health problems to further understand how changes in a system can lead to changes at the individual level. Policy makers should be aware of the interdependencies and interactions between health and non-health sectors and engage in intersectoral collaborations to come to effective interventions. However, a practical guide for local and national governments on system approaches and multidisciplinary collaboration is currently lacking and should be developed to improve integrated area development in the future. Also, (local) governments should be aware that integrated area development may lead to additional questions regarding the physical borders of a project; new developments be must be properly adjusted to existing areas, to prevent that these developments have a detrimental effect on other adjacent areas.

Participatory design instruments can help organize the conditions for achieving desired outcomes. For (local) governments, this means that common policy instruments, such as cost-benefit and cost-effectiveness analyses [303], require additional multidisciplinary and participatory instruments to tailor policy design to specific local conditions. Also, when the design phase is completed, market parties usually take over for the execution of the plans. In this phase, health-relevant decisions are made as well, but participation is mostly not obligatory anymore. To prevent that public values are ignored because of costs or other private interests, municipalities can provide clear requirements for ongoing participation to the project developer or contractors that wins the tender.

When consulting the public through participatory instruments, it is crucial to involve all subgroups in society as relationships between environment and behavior can be different for different subgroups. In the future, close collaboration between researchers and policymakers is necessary to investigate how research could better inform policy makers about the expected effects of built environment changes on health.

Conclusions

Based on the results of the studies in this dissertation, we can conclude that the Green Carpet has an impact on the physical activity behaviors of individuals that are exposed to this new environment, especially on transport-based physical activity and sedentary behavior. The effects of the newly designed area on transport-based physical activity increased over time, indicating that changes to the environment are a sustainable way to change behavior. However, it should be taken into account that relationships between (perceptions of) the environment and behavior very across different subgroups in society. While for more vulnerable individuals the absence of physical barriers might be an important predictor for physical activity, for less vulnerable individuals the presence of several facilitating factors is associated with more physical activity. In the light of socioeconomic health inequalities, it is important to consider these differences when designing new areas and adopt an integral approach targeting both barriers and facilitating factors for physical activity.

In conclusion, the research in this dissertation showed that healthy urban area reconstruction has a positive effect on transport-based physical activity and decreases transport-based sedentary behavior of the inhabitants of the affected area.

APPENDICES

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SUMMARY

The city of Maastricht used to be crossed by a highway, which formed a physical and social barrier between the neighborhoods east and west of it. In 2016, a 2.3-km long double-layered tunnel was constructed to replace the highway and facilitate the passing traffic. On top of this tunnel, two one-way streets were created to accommodate the remaining local traffic. The two one-way streets are separated by a middle part, which is prioritized for pedestrians, cyclists and recreation. The middle part is separated from the adjacent streets by grass and trees, creating the so-called 'Green Carpet'. The aim of the research presented in this dissertation was to evaluate the effects of the Green Carpet in Maastricht on physical activity, sedentary behavior and health-related quality of life. In addition, we aimed to explore differences in the relationship between the environment and behavior for more or less advantaged individuals in society. Lastly, we evaluated the effect of contextual factors on the design, execution and evaluation of the Green Carpet project.

Chapter 2 describes the results of the systematic review. The aim of the systematic review was to examine the effect of built environment infrastructural changes (BEIC) on physical activity, active transport and sedentary behavior. A literature search in two electronic databases resulted in nineteen eligible articles. BEICs were separated in two categories: on- and off-road bicycling and/or walking trails, and more extensive BEICs involving changes in the larger (infrastructural) system. The results showed that on- and off-road bicycling and/or walking trails resulted in inconsistent effects on overall PA and walking, and in predominantly positive effects on bicycling. The more extensive BEICs led to mixed results, with mainly non-significant effects. However, positive effects on bicycling were found for people living closer to the BEICs. Remarkably, none of the studies assessed the effect on sedentary behavior. The risk of outcome measurement bias and bias in the selection of reported results was higher in the studies that evaluated smaller on- and off-road walking and/or bicycling trails in comparison to the more extensive infrastructural interventions. So, studies with a higher risk of bias were more likely to report significant changes in outcomes than studies with a lower risk of bias. To improve the understanding of the potential of BEICs to increase physical activity levels and decrease sedentary behavior at population-level, more high-quality research is needed. Future research should consider the use of context-specific measurements, provision of detailed description of the context in which an intervention takes place, and the inclusion of multiple groups based on the proximity to the intervention.

Chapter 3 describes how the context of mid- and long-term urban reconstructions such as the Green Carpet influences design and implementation conditions that prove crucial to project achievement. The socioeconomic and geographical context were especially of importance during the agenda setting phase. The geographical context influenced the planning procedure due to the physical location of the city, which is bordered by protected natural areas. The poor socioeconomic position of neighborhood bordering the Green Carpet stressed the need for change in this area. The project had to follow existing legal frameworks, which makes that this context shaped the initial project. The political context evoked most of the changes during the planning and implementation phases, due to the political agency of specific stakeholders, national policies, and obligatory and voluntary consultations of the inhabitants and stakeholders. The changes in the context influenced the design and implementation conditions that prove crucial to project achievement. Due to the constant interactions between context and the project, impacts can hardly be ascribed to the initial project. Traditional evaluation designs often ignore these process dynamics in order to maintain 'study design fidelity'. To improve the internal validity, interpretation and implications of future evaluations, we recommend adopting a complex systems approach and mixed methods design that enable investigating the interactions between the project and its context.

In **chapter 4 and 5,** the relationships between the perceived neighborhood walkability and (context-specific) physical activity levels are presented. The results of the baseline measurements of the effect evaluation showed that more physical activity-supportive environments such as the presence of places to go within walking distance and the presence of attractive buildings are associated with less sedentary behavior and an increase in moderate-to-vigorous physical activity, but might not affect light physical activity (**chapter 4**). However, the potential of the built environment to affect physical activity levels differed for more and less advantaged individuals in society (i.e. lower educated individuals and higher educated individuals). For less advantaged individuals, the absence of (physical) barriers (i.e. highways, railways, traffic) might lead to more physical activity and less sedentary behavior. For more advantaged individuals, the presence of physical activity supporting elements (i.e. aesthetics, presence of destinations) was found to be associated with more physical activity. Further, context-specific analyses of the data showed that associations between perceived neighborhood walkability and neighborhood-based physical activity depends on the time that is spent in the home neighborhood (**chapter 5**). Perceived neighborhood walkability only affected neighborhood-based physical activity levels for those who spent relatively more time in their home neighborhoods. Physical activity facilitating features in the home neighborhood were only associated with more neighborhood-based physical activity for more advantaged individuals. These findings imply that the same physical environment might have different effects on more and less vulnerable individuals.

The effects of the Green Carpet on physical activity, active transport and sedentary behavior at the first follow-up are presented in **chapter 6**. At this relative short term, no increases in total or transport-based physical activity levels were found for the minimal and maximal exposure groups in Maastricht. However, a decrease in transport-based MVPA and increase in transport-based SB was observed in the no exposure group. This might be an indication that the Green Carpet prevents the increase in transport-based SB over time. Subgroup analyses showed that the area-based differences might reflect the differences between users and non-users, but this should be interpret with caution, due to potential selective mobility bias.

Spatial analyses in **Chapter 7** show that the changes in the environment changed the physical activity patterns of the residents that lived in the adjacent neighborhood. This might indicate a rerouting of pre-existing travel, or an actual shift in physical activity behavior that will eventually lead to increases in the volume of total daily physical activity, as a result of prolonged favorable physical activities such as active transport. These results show 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. Also, both lower and higher educated individuals tended to use the new infrastructure at the first follow-up. So, such major infrastructural projects can influence the behavior of different subgroups in society. 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, particularly to improve our insights in creating impact for vulnerable populations.

Chapter 8 discusses the results of the longer-term follow-up measurements of the effect evaluation. The aim of this evaluation was to assess the longer-term effects of the Green Carpet on physical activity, sedentary behavior, active transport and health-related quality of life at 29-39 months after the official opening of the Green Carpet. The results show significant intervention effects on transport-based sedentary behavior and transport-based light intensity physical activity for both exposure groups, compared to the no exposure group. In comparison to the shorter-term evaluation and despite the COVID-19 physical isolation policies, the effect sizes increase over time. These results emphasize the potential of the built environment in changing and sustaining healthy behavior over a longer period of time. Social participation and meaningfulness increased in the maximal exposure group while it decreased in the minimal and no exposure groups, but changes

were not statistically significant. As the intervention area is still under construction, even longer follow-up terms might be needed to explore its full potential.

Finally, **chapter 9** summarizes the main findings, discusses the theoretical and methodological considerations, and presents implications and recommendations for future research and practice. We conclude that the built environment has an impact on the physical activity behaviors of individuals who live in this environment, especially on physical activity and sedentary behavior during transport.

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SAMENVATTING

Het oosten van de stad Maastricht werd jarenlang doorkruist door de snelweg A2, die een fysieke en sociale barrière vormde voor de aangrenzende wijken en een negatieve invloed had op de gezondheid van de inwoners. In 2016 werd het stuk snelweg dat Maastricht doorkruiste vervangen door een 2.3 kilometer lange dubbellaagse tunnel, die het verkeer sindsdien onder de stad door leidt. Om het lokale verkeer te faciliteren zijn bovenop de tunnel twee éénrichtingsstraten gerealiseerd. Deze éénrichtingsstraten zijn gescheiden door een onverhard middengedeelte, speciaal ontworpen voor voetgangers, fietsers en recreatie. Het middengedeelte is gescheiden van de rijbanen door gras en bomen, waarmee de zogenoemde Groene Loper is gecreëerd.

Het doel van het onderzoek in deze thesis was het evalueren van de effecten van de Groene Loper op beweeggedrag, zitgedrag en de aan gezondheid gerelateerde kwaliteit van leven. Daarnaast onderzochten we de verschillen in de relatie tussen de gepercipieerde beweegvriendelijkheid van de leefomgeving en beweeggedrag voor meer en minder kwetsbare individuen in de samenleving. Ook evalueerden we hoe contextuele factoren effect hadden op het design, de uitvoering en de evaluatie van het Groene Loper project.

Hoofdstuk 2 beschrijft de resultaten van een systematisch literatuuronderzoek. Het doel van deze studie was het onderzoeken van de effecten van infrastructurele veranderingen in de gebouwde omgeving op fysieke activiteit, zitgedrag en actief transport. Een zoekopdracht in twee elektronische databanken resulteerde in negentien geschikte artikelen. De infrastructurele veranderingen in deze artikelen werden onderverdeeld in twee categorieën: 1) fietsstroken en fiets/wandelpaden en 2) uitgebreidere aanpassingen met veranderingen in het grotere (infrastructurele) systeem. De resultaten toonden aan dat het aanleggen van fietsstroken en fiets/wandelpaden resulteerde in inconsistente maar overwegend positieve resultaten op actief transport. De uitgebreidere infrastructurele aanpassingen leidden tot wisselende resultaten met voornamelijk niet-significante effecten. Wel werden positieve effecten gevonden op actief transport, maar alleen voor mensen die dichter bij de nieuwe infrastructuur woonden. Echter, er moet rekening worden gehouden met vertekening van de resultaten doordat de kwaliteit van de studies die fietsstroken en fiets/wandelpaden evalueerden van lagere kwaliteit waren dan de studies die uitgebreidere infrastructurele interventies evalueerden. Studies met een hoger risico op bias rapporteerden eerder significante veranderingen in uitkomsten dan studies met een lager risico op bias. Om meer inzicht te krijgen in het potentieel van grote infrastructurele veranderingen om fysieke activiteitenniveaus te verhogen en zitgedrag gedrag te verminderen, is meer onderzoek van hoge kwaliteit nodig.

Toekomstig onderzoek moet bij voorkeur een gedetailleerde beschrijving geven van de context waarin de interventie plaatsvindt, gebruik maken van context-specifieke metingen en gebruik maken van meerdere onderzoeksgroepen op basis van de afstand tussen de woonplaats en de omgevingsinterventie.

Hoofdstuk 3 beschrijft hoe de context van middellang- tot langdurende projecten in de fysieke leefomgeving invloed heeft op het design en de implementatieomstandigheden van het project. In de casus van de Groene Loper onderzochten we aan de hand van kwalitatieve stakeholderinterviews en documentanalyse de rol van verschillende typen context aan de hand van het CICI-framework. De sociaal-economische en geografische context bleken vooral belangrijk bij het agenderen van de situatie rondom de A2 in Maastricht op landelijk niveau. De geografische context had invloed op het uiteindelijke design door de fysieke locatie van de stad Maastricht; de stad wordt omringd door beschermd natuurgebied en daarmee werd het aantal mogelijke oplossingen verkleind. De slechte sociaaleconomische status van de wijken grenzend aan de Groene Loper legde de relatie met het belang van het project voor het welzijn van de inwoners. Daarnaast moest het project zich aan de bestaande wettelijke kaders houden, waardoor de juridische context belangrijk was voor het vormgeven van het oorspronkelijke project. De politieke context zorgde voor de meeste veranderingen gedurende de fasen van planning en uitvoering, voornamelijk door strategisch gedrag van verschillende stakeholders, maar ook door nationaal beleid en door verplichte en vrijwillige consultaties van inwoners en stakeholders in het plangebied. Zo werd er een “Gentlemen’s Agreement” gesloten tussen het Projectbureau A2 Maastricht en het A2 Buurten Platform, welke resulteerde in het realiseren van een geluidswal en meer draagvlak voor het project in de aangrenzende buurten. Door de continue interacties tussen de context en het project is het onmogelijk om de impact van de omgevingsveranderingen op leefbaarheid en gezondheid alleen toe te schrijven aan het project zelf. Traditionele onderzoeksdesigns negeren deze dynamische processen vaak om onderzoek reproduceerbaar te houden. Echter, om de interne validiteit, interpretatie en implicaties van toekomstige evaluaties te verbeteren, is een systeemaanpak nodig waarin kwalitatief en kwantitatief onderzoek gecombineerd wordt om zich te krijgen op de samenhang tussen een project, de context en veranderingen daarin over tijd.

In **hoofdstuk 4 en 5** worden de relaties tussen de beweegvriendelijkheid van de woonomgeving en fysieke activiteiten niveaus gepresenteerd. De resultaten van de beweegmeting en het vragenlijstonderzoek tijdens de nulmeting lieten zien dat een meer beweegvriendelijke omgeving met meer bestemmingen binnen loopafstand en de aanwezigheid van aantrekkelijke gebouwen, was geassocieerd met minder zitgedrag en meer matig-tot-zwaar intensieve fysieke activiteit van de deelnemers. Deze associaties waren echter verschillend voor meer en minder kwetsbare individuen in de samenleving (bijvoorbeeld lager opgeleide individuen of personen met gezondheidsproblemen). Voor meer kwetsbare individuen in de maatschappij is de afwezigheid van (fysieke) barrières zoals snelwegen, treinrails en verkeer geassocieerd met meer fysieke activiteit en minder zitgedrag. Voor minder kwetsbare individuen is vooral de aanwezigheid van elementen die fysieke activiteit stimuleren gerelateerd aan meer beweeggedrag en minder zitgedrag, zoals een goede esthetiek (bijvoorbeeld aantrekkelijke gebouwen) en de aanwezigheid van bestemmingen (bijvoorbeeld cafés, winkels). Daarnaast lieten context-specifieke analyses zien dat de relatie tussen de beweegvriendelijkheid van de woonomgeving en fysieke activiteit in de woonomgeving afhankelijk is van de tijd dat men in zijn of haar woonomgeving spendeert. De ervaren beweegvriendelijkheid van de woonomgeving was dan ook alleen geassocieerd met beweeggedrag in de woonomgeving voor diegenen die daar relatief veel tijd doorbrengen. Ook bleek opnieuw dat de aanwezigheid van elementen die de fysieke activiteit stimuleren alleen geassocieerd was met meer fysiek activiteit in de woonbuurt voor de minder kwetsbare individuen in de samenleving.

De korte-termijn effecten van de Groene Loper op fysieke activiteit, actief transport en zitgedrag zijn gepresenteerd in **hoofdstuk 6**. Op relatief korte termijn, 3 tot 15 maanden na de opening van de Groene Loper, waren geen significante verschillen zichtbaar op de totale hoeveelheid fysieke activiteit van de inwoners van de wijken rondom de Groene Loper. Echter, we zagen bij de deelnemers in de controlegroep een afname van de hoeveelheid matig-tot-zwaar-intensieve fysieke activiteit tijdens transport en een toename van de hoeveelheid zitgedrag tijdens transport. Dit kan een indicatie zijn dat de Groene Loper een afname van fysieke activiteit tijdens transport voorkomt. Subgroep analyses toonden aan dat de verschillen in de resultaten voor de groepen in Maastricht en Heerlen gebaseerd kunnen zijn op de verschillen in beweeggedrag tussen gebruikers en niet-gebruikers van de Groene Loper.

De ruimtelijke analyses in **hoofdstuk 7** lieten zien dat de veranderingen in de omgeving zorgden voor een verandering in de beweegpatronen van de inwoners van de wijken rondom de Groene Loper. Dit gebeurde ondanks dat er in de korte-termijn evaluatie nog geen significante effecten op de totale hoeveelheid fysieke activiteit en totale hoeveelheid actief transport gevonden werden. Dit kan wijzen op een verandering in de routes die men neemt, of op een daadwerkelijke verandering in gedrag die op lange termijn kan leiden tot toename van de hoeveelheid totale fysieke activiteit en actief transport. De resultaten toonden aan dat het volgen van een integrale aanpak die zich richt op meerdere omgevingsaspecten zoals een verbeterde verkeersveiligheid, connectiviteit en hoeveelheid groen, op korte termijn kan leiden tot veranderingen in de manier waarop openbare ruimtes gebruikt worden. Ook toonden we aan dat zowel lager als hoger opgeleide personen de nieuwe infrastructuur gebruikten. Dit impliceert dat grote infrastructurele projecten het gedrag van verschillende subgroepen in de samenleving kunnen beïnvloeden. Het onderzoek laat zien dat veranderingen in de gebouwde omgeving kunnen leiden tot veranderingen in gedrag, maar dat dit niet noodzakelijkerwijs leidt tot meetbare veranderingen van beweeggedrag op populatieniveau. Als we in de toekomst beter willen begrijpen hoe de fysieke omgeving gedrag en gezondheid beïnvloedt, zijn daarom meer diverse vormen van gegevensverzameling en analysemethoden nodig.

Hoofdstuk 8 bevat de resultaten van de tweede nameting van de effectstudie. Het doel van dit hoofdstuk was het evalueren van de langere-termijn effecten op 29-39 maanden na de opening van de Groene Loper op fysieke activiteit, zitgedrag, actief transport en de aan gezondheid gerelateerde kwaliteit van leven van gebruikers van dit gebied. De resultaten lieten een significante afname zien van zitgedrag tijdens transport en een significante toename van lichte fysieke activiteit tijdens transport. Dit werd gevonden voor zowel de groep met maximale blootstelling aan de Groene Loper als de groep met minimale blootstelling, in tegenstelling tot de groep zonder blootstelling aan de Groene Loper. In vergelijking met de kortere-termijn evaluatie werden de effecten op gedrag groter gedurende de tijd, ondanks de contactbeperkende COVID-19 maatregelen die gedurende een deel van de nametingen van kracht waren. De resultaten lieten zien dat de gebouwde omgeving de potentie heeft om gedrag te veranderen en dit nieuwe gedrag uit te bouwen en te behouden over een langere periode. De scores op sociale participatie en zingeving namen toe in de groep met maximale blootstelling aan de Groene Loper, terwijl deze afnamen in de groepen met minimale of geen blootstelling. Echter waren deze veranderingen niet statistisch significant. Aangezien het interventiegebied nog altijd in ontwikkeling is, zijn meer nametingen aanbevolen om de volledige potentie van gebiedsverandering te onderzoeken.

Ten slotte werden in **hoofdstuk 9** alle resultaten van de onderzoeken samengevat en bediscussieerd in een theoretisch en methodologisch perspectief. Daarnaast werden de implicaties van het onderzoek besproken en werden er aanbevelingen gedaan voor onderzoek en praktijk. In dit hoofdstuk kwamen onder andere het belang van het combineren van kwalitatief en kwantitatief onderzoek, het toepassen van een systemische onderzoeksaanpak, de rol van de sociale omgeving en het belang inwonersparticipatie aan bod. De hoofdconclusie van deze thesis is dat de gebouwde omgeving een impact heeft op fysieke activiteit van de inwoners van deze omgeving, met name op fysieke activiteit en zitgedrag tijdens transport.

IMPACT PARAGRAPH

The research in this dissertation assessed the effects of the built environment on physical activity, sedentary behavior, active transport and health-related quality of life in adults. A natural experiment evaluated the effects of the Green Carpet in Maastricht, which is a newly built infrastructure prioritized for pedestrians, cyclists and recreation, built on a tunnel that replaced a cross-town highway. The studies in this dissertation showed significant intervention effects on transport-based physical activity and also changes in physical activity behavioral patterns were identified. No significant changes on health-related quality of life, social activities and meaningfulness were found, but trends were positive for the inhabitants living close to the intervention area, compared to individuals living further away. This paragraph reflects on the scientific and societal impact of these findings.

Scientific impact

This is one of the first research projects that investigated the effects of the environment on physical activity and active transport using device-based methods with a follow-up time of two to three years. The results showed intervention effects for transport-based physical activity levels, and effects increased over time. This shows that for such large infrastructural projects, it takes a large amount of time to result in measurable behavioral changes. However, if changes occur, these are likely to be sustainable over time. Future research should consider follow-up times of at least two years when investigating large infrastructural projects. Also, another unique characteristic of this dissertation is the broad range of research methods that was applied to investigate the broader system in which the Green Carpet was implemented and evaluated. The evaluation of the context and the addition of an ethnographic and participatory research approach resulted in a better understanding of the results of the quantitative evaluation and showed the complexity of the relationship between environment and behavior. Future research should continue to evaluate intervention, implementation and context in interaction, by applying a systems approach. Lastly, our cross-sectional analyses showed differences in the relationship between perceptions of the environment and behavior for less and more vulnerable individuals in society. It is clear that the environment is not a one-size-fits-all solution for behavioral change. Even though this is highly relevant in the light of reducing socioeconomic health inequalities, these subgroups are rarely studied. Our studies showed that despite the differences in the relationship between perceptions of the environment and behavior, an integral approach targeting both barriers and facilitators of physical activity in the environment can lead to equal use of new infrastructures by different subgroups in society.

Most studies presented in this dissertation are published in international, peer reviewed, scientific journals. In addition, the results of the studies were presented at various (inter) national scientific conferences, such as the conference of the International Society of Behavioral Nutrition and Physical Activity, the conference of the International Society of Physical Activity and Health, and at the International Conference on Ambulatory Monitoring of Physical Activity and Movement. Also, the research in this dissertation was used for educational activities in the master of Health Education and Promotion of Maastricht University.

Societal relevance

The tunneling of the highway A2 and the construction of the Green Carpet had an impact on the lives of inhabitants living in the neighborhoods bordering the former highway. The livability in these neighborhoods improved with better air quality, noise reduction and decreased traffic congestion. Also, the connectivity with the city center was enhanced and new facilities at the Green Carpet such as fitness equipment, restaurants and bars improved the liveliness in the area. The results of the studies in this thesis showed that these changes in the environment resulted in changes in physical activity behavioral patterns and changes in active transport. However, the highway was not only a physical barrier between the neighborhoods east and west of it, but also a social barrier. Although the physical barrier is broken, the social barrier seems to be still in place. The communities that were separated for years seem to struggle to reconnect. As the social environment is equally relevant for health and health behaviors as the physical environment, local governments should put effort in the reconnection of the neighborhoods in a social sense. Inhabitants of one of the neighborhoods bordering the Green Carpet already acted on that. This neighborhood did not benefit from the implementation the Green Carpet and used the output of the ethnographic research and inhabitants meeting as an input for a grant application for the local government, to improve the livability in this specific neighborhood.

In the future, the new Environment and Planning act of the Netherlands (Omgevingswet) will be implemented. This new act simplifies the existing system of legislation for the development and management of the living environment. This will be done by bundling dozens of laws and hundreds of rules into one new law. One of the societal objectives of this new law is creating a healthy physical environment. It is stated that a healthy living environment invites healthy behavior and protects against negative environment influences. The current research project can help to inform local, regional and national governments about the relationship between the environment and health (behaviors) in the Dutch context, to include health in their future developments. The present dissertation underlines that infrastructural changes do not only impact the esthetics and attractiveness of a city or region. They can have a significant impact on the health of people. The Green Carpet may serve as an example of how environmental restructuring can be a powerful tool for (local) governments to increase the health and well-being of its inhabitants.

The results of our studies are presented to the public via various ways. A residents meeting was organized to discuss the results with inhabitants of a specific neighborhood in Maastricht. Results were also presented to inhabitants and other interested parties during the Pleasure Arts and Sciences Festival in Maastricht (2022). Further, results were disseminated to other researchers and policymakers during a symposium of the ZonMw consortium Maak Ruimte voor Gezondheid.

APPENDICES

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CURRICULUM VITAE

Nicole Stappers was born on August 12th, 1992 in Meijel, The Netherlands. After finishing her senior general secondary education in 2010, she started the bachelor Medical Technology (Biometrie) at Zuyd Hogeschool of Applied Sciences in Heerlen. She received her bachelor's degree (cum laude) in July 2014 and graduated from the master Human Movement Sciences at Maastricht University in July 2015.

After her education, she started working at the Research & Statistics department of the municipality of Maastricht. In April 2016 she returned to Maastricht University to work as a research assistant at the department of Health Promotion, where she performed the baseline measurements of the studies presented in this dissertation. In 2018, she officially started her PhD trajectory, focusing on the effects of the physical and social environment on physical activity and health. She did this using a natural experiment evaluating the tunneling of the highway A2 and the construction of the Green Carpet on top of it, in the city of Maastricht. The results of the effect- and process evaluations are presented in this dissertation.

Nicole is currently working as a postdoctoral researcher at Radboud University Medical Center in Nijmegen and the National Institute for Public Health and the Environment (RIVM).

PUBLICATION LIST

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Stappers, N.E.H., Schipperijn, J., Kremers, S.P.J., Bekker, M.P.M, Jansen, M.W.J., De Vries, N.K., Van Kann, D.H.H. (2022). Visualizing changes in physical activity behavioral patterns after redesigning urban infrastructure. Health and Place, 76, 102853.

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