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Energimyndigheten

Preface

The United Nations Agenda 2030 highlights the importance of making cities available for all citizens, through providing access to safe, affordable, accessible and sustainable transport systems, with special attention to the needs of those in vulnerable. Walking and cycling are promoted as sustainable, healthy, and inclusive modes of transportation, as well as a tool to make cities more resilient. Walking and cycling may in particular substitute short motor vehicle trips, thereby reducing energy usage and CO2-emissions, decreasing noise and air pollution, and improving living conditions on a local level. The BELYSA-project provides theoretical understanding and methodological approaches as well as results from evaluated on-site implementations of electric lighting along shared walk and cycle paths. The study outcomes may contribute to improve the quality of travel for pedestrians and cyclists especially during dark hours.

The BELYSA-project was funded by the Swedish Energy Agency grant Dnr: 48141-1, during the period 2019-2022, and due to the Covid-19 pandemic extended to 2024. The research team was multidisciplinary and included researchers from Environmental Psychology, Department of Architecture and Built Environment, Lund University, Transport and Roads Division, Department of Technology and Society, Lund University and Infrastructure Maintenance at the Swedish Road and Transport Institute (VTI).

The research was carried out in collaboration with Linköping Municipality and Lund Municipality. The municipalities served as important discussion partners, decided on and fully funded the implementation of interventions. We would especially like to thank Elna Hammarström Linköping Municipality, and Mats Lawesson and Anders Bengtsson Lund Municipality.

We give our special thanks to all colleagues who have provided support along the way: Georgios Tsiakiris at Environmental Psychology, Lund University, Carl Johansson, Kevin Gildea and Lisa Hiselius at the Transport and Roads Division, Lund University, and Leif Sjögren, Jenny Eriksson, Mattias Thunberg, Martin Larsson, Peter Andrén, Harry Sörensen, Claudia Bratu and Linda Corper at the Swedish National Road and Transport Research Institute.

Lund April 2024

Maria Johansson on behalf of the BELYSA research team

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Sammanfattning

I länder på nordliga breddgrader varierar förutsättningarna att pendla till fots eller med cykel med årstiderna. Forskningsprojektet BELYSA syftar till att förbättra resekvaliteten för fotgängare och cyklister när det är mörkt ute. Projektet integrerar tekniska mätningar och observationsbaserade bedömningar av gång- och cykelvägar med videoinspelning av beteenden. Projektresultaten inkluderar teoretisk och metodologisk utveckling samt utvärdering av olika interventioner (förändringar i utformning och vägyta, beskärning av grönska samt ny belysning) längs gång- och cykelvägar i Linköping och Lund.

BELYSA-projektet bidrar till kunskapsutvecklingen om hållbara transporter genom att parallellt jämföra fotgängares och cyklisters miljöupplevelser och beteende i både dagsljus och elektrisk belysning. Resultaten visar att det finns en skillnad i hur de två grupperna uppfattar och upplever miljön under olika ljusförhållanden. Cyklister bedömer kvaliteten på vägytan som sämre än vad fotgängare gör. Fotgängarna är mer oroade för sin trygghet än vad cyklisterna är längs samma sträcka. De två grupperna är också olika känsliga för förändringar i miljön såsom ny vägbelysning. Resultaten är baserade på cirka 600 deltagare i Linköping och Lund som har medverkat i strukturerade vandringar och/eller besvarat frågeformulär.

Resultaten ger också starka indikationer på att fotgängares och cyklisters rörelsemönster påverkas olika av miljöinterventioner. Begreppet ”slalomrörelse” som beskriver hur fotgängare och cyklister avviker och vinglar längs en given rutt visar hur utformning och belysning kan minska slalomrörelser hos både fotgängare och cyklister. Däremot bidrog interventionerna till att cyklisterna ökade hastigheten, medan den motsatta effekten sågs hos fotgängare, de sänkte hastigheten. Rörelsemönster har analyserats med hjälp av videoinspelningar från drönare, omfattande cirka 200 flygningar om vardera 20 minuter.

Tekniska mätningar av miljöinterventionerna har genomförts med hjälp av en cykelmätvagn. Denna mätvagn är en prototyp framtagen vid VTI och vidareutvecklad inom projektet för att (med en linjelaser) i cykelhastighet kontinuerligt kunna mäta vägytans jämnhet i både tvär- och längsled. Det är också möjligt att samtidigt göra en kontinuerlig ljusmätning (Illuminans) i tre olika riktningar längs en cyklad sträcka utan att hindra andra trafikanter.

BELYSA-projektet visar på vikten av att stadsplanering och utformning av infrastruktur tar olika grupper i beaktning. Miljöförändringar måste stödja både fotgängare och cyklister under alla årstider samt dygnets ljusa och mörka timmar.

Summary

In the Nordic context, the seasonal variation provides very different conditions for pedestrian and cyclist commuters over the year. The BELYSA-project aimed to improve the quality of travel for pedestrians and cyclists during dark hours. The project integrated technical environmental assessments (TEA), and observer-based environmental assessments (OBEA) of walk and cycle paths with video recordings of behaviour. The project outcomes include theoretical and methodological developments as well as results from evaluations of environmental interventions (changes in layout and surface, maintenance of greenery and new electric lighting) on-site in Linköping and Lund.

A major contribution of the BELYSA-project is the results from parallel comparisons of pedestrians' and cyclists' environmental experiences and behaviour in day light and electric lighting conditions. It is shown that the two groups to some extent differ in how they perceive and experience shared walk and cycle paths in daylight and electric lighting conditions.
Cyclists assess surface quality as lower than do pedestrians, whereas pedestrians are more concerned about their personal safety than what cyclists are along the same path. These groups also partly differ in their experience of environmental interventions such as new electric lighting. The results are based on about 600 participants in structured walks and/or questionnaires studies on site in Linköping and Lund.

The results also indicate that pedestrians and cyclists respond differently in their microscopic behaviour, to the environmental interventions introduced. The new concept of slalom, capturing deviations from the straight (most efficient) travelling path, suggests that the interventions decrease slalom among both pedestrians and cyclists. However, while cyclists increase speed, the opposite trend is identified for pedestrians who reduce speed after the introduction of environmental interventions. These results were obtained from analyses of video recordings collected by about 200 drone flights of 20 minutes each

The Bicycle Measurement Trailer (BMT) was used to measure and describe the environmental interventions. BMT is a prototype developed at VTI to facilitate condition assessment on cycle paths. The BMT was further developed within the BELYSA-project and used to perform dynamic and continues measurements of illuminance along the path, surface texture and evenness at normal cycling speeds, without interfering with the traffic or preventing other road users from accessing the cycle path.

The BELYSA-project suggest that the development towards more sustainable travel calls for improvements in infrastructure for pedestrians and cyclists. The outcomes show that it is essential to consider different user groups, seasons and times of day if we are to reach the full potential of urban planning and design in a shift towards more sustainable urban travel. This implies that improvements must be valid for both pedestrians and cyclists and during daylight and dark hours.

Background

The United Nations Agenda 2030 highlights the importance of making cities available for all citizens, through providing access to safe, affordable, accessible and sustainable transport systems, with special attention to the needs of those in vulnerable situations (e.g. women, children, persons with disabilities and older persons) (United Nations, 2015). Recently, walking and cycling are promoted as not only sustainable, and healthy, but also as an important link in sustainable intermodal transportation systems (Rastogi, 2011), an inclusive modes of transportation, and as a tool to make cities more resilient to pandemics (Hasselwander et al., 2021). Walking and cycling may in particular substitute short motor vehicle trips, thereby reducing energy usage and CO2-emissions, decreasing noise and air pollution, and improving living conditions on a local level (Wilson et al., 2007; Xia et al., 2015).

On the European and national level, the European Commission's Sustainable Urban Mobility Plan SUMP (Wefering et al., 2014) and the Swedish Trafik för en Attraktiv Stad (TRAST) (Swedish Transport Administration, 2015) are guidelines aimed at helping decision-makers to adopt strategies for creating sustainable cities, through a shift towards more sustainable modes of transport, such as walking and cycling. The particular role of cycling for a sustainable society is emphasized by the Swedish Government in the national cycling strategy for more and safer cycling (Näringsdepartementet, 2017). The strategy points out the need for research and innovation that can contribute to an increased knowledge of the effects of different measures to increase cycling. In Sweden, the number of bicycle trips decrease by half from summer to winter, and darkness is one the reasons for this (Bergström & Magnusson, 2002). So far, choice of transportation has largely been studied by means of social psychological theories, such as the Theory of Reasoned Action and Theory of Planned Behavior (Hoffmann et al., 2017). However, pedestrians and cyclists directly interact with the surrounding built environment, and they tend to evaluate their trips in terms of the presence or absence of certain environmental features, such as trees (Stradling et al., 2007).

A solid bulk of knowledge is available about macro-level factors that promote (or discourage from) walking and cycling (Pucher & Buehler, 2017), and on the impact of neighborhood-level built environment characteristics (such as density, diversity and design of the built environment) on people's level of physical activity and travel mode choices (Ewing & Cervero, 2010). On the other hand, the knowledge on how micro-level environmental factors, such as design characteristics and maintenance status of walking/cycling facilities, affect the quality of a trip, is less certain. Little is known about how the perception of such micro-level factors influences pedestrians and cyclist behaviour, especially at twilight and dark hours. The existing knowledge is scattered over several research areas, but there seems to be a common expectation that by providing outdoor lighting the conditions for pedestrians and cyclists after sunset may approach the daytime conditions. Well-designed outdoor lighting would thus prolong the season for commuting by bike or by walking with an increase of the overall amount of walking and cycling as a result (Addy, 2004; Jago, 2005; Lee, 2008; Rosenberg et al., 2013; Fotios, 2019). From a sustainability perspective, it is important to consider energy-saving aspects and non-human species when designing transport lighting, such as by minimizing light pollution (Jägerbrand & Spoelstra, 2023) and energy use (Rahm, 2019; Beccali et al., 2018; Johansson et al., 2014).

Still, there is an urgent need for transdisciplinary approaches in order to i) in parallel understand how micro-level environmental factors may support or hinder walking and cycling during both daylight and dark hours ii) translate such insights into practices that adequately meet the needs among pedestrians and cyclists, and iii) evaluate the intended impact of implementations carried out on pedestrian and cyclist behaviour.

Departing from theories on human-environment interaction to understand energy-use behaviour, the BELYSA-project focuses on how electric outdoor lighting may serve to improve the quality of travel for pedestrians and cyclists and thereby possibly prolonging the season for these sustainable modes of transportation. Increasing the likelihood of replacing short motor vehicle trips with active, sustainable forms of transport would bring about a net reduction in energy usage, since the gains associated with reduction in motorised travel is expected to exceed the costs associated with the replacement of old lighting installations with new, energy-efficient technology, such as light emitting diodes (LED-light sources).

Micro-level environmental factors and walking and cycling

Various disciplines exploring environmental factors supporting walking and cycling, e.g. architecture and urban design (Southworth, 2005; Sugiyama & Ward Thompson, 2008; Ewing & Handy, 2009), environmental psychology (Alfonzo, 2005; Brown et al., 2007; Johansson et al., 2011; Johansson et al., 2016), health sciences (Frank et al., 2006; Owen et al., 2004; Sundquist et al., 2011), and transport research (Manaugh & El-Geneidy, 2011; Millward et al., 2013), have approached the task at different scales. A common approach has been to focus on the neighbourhood level of the built environment, for example in terms of density, diversity, design, destination accessibility, and distance to transit (Ewing & Cervero, 2010). Another approach has been to focus on micro-level factors, such as traffic, street width, and slope (Handy, 2005). Internationally, temporary design solutions have been introduced to facilitate walking/cycling in urban areas (e.g. Rollin and Bamberg, 2021). Successful implementation of design solutions aimed at increasing the modal promotion of walking/cycling requires an integrated understanding of what works and what does not. This implies that design must support the needs of pedestrians and cyclists. So far, the research field(s) on walking/cycling have largely treated these travel modes separately despite pedestrians and cyclists often sharing the same space, or have their space divided by road markings (e.g. Barnett et al., 2017; Kellstedt et al., 2021).

Several instruments exist that assess neighbourhood characteristics considered important for both walkability and bikeability (for instance Systematic Pedestrian and Cycling Environmental Scan (Pikora et al., 2006); Neighbourhood Environment Walkability Scale (Saelens et al., 2003) and the Active Commuting Route Environment Scale developed in a Swedish context (Wahlgren et al., 2010)). These instruments are however not sensitive enough to distinguish between daylight and electric light conditions, or between different lighting designs. They disregard the psychological process beyond environmental perception, such as the interplay between environmental experiences and attitudes. Singularly they lack in detail in order to point to implement needed interventions in micro-level environmental factors. A thorough understanding is needed of the micro-level factors per se, and how these factors interact with pedestrian and cyclist behaviour on the paths.

Environmental assessment: TEA and OBEA

Assessment of micro-level environmental factors can broadly be categorised into technical environmental assessment (TEA) and observer-based environmental assessment (OBEA) (Craik & Feimer, 1987; Gifford, 2007). TEA involves tools and measures (metrics) to produce a reading of environmental quality e.g. illuminance in lux or noise in dBA, and is usually referred to as “place-centred” and “objective”. In the present context TEA refers to functional requirements regulating road lighting performance such as luminance [cd/m^2], illuminance [lx], glare and uniformity (SS-EN 13201-3:2016). Illuminance describes the ability of road lighting to illuminate objects and is related to the “brightness” perceived by road users. Luminance describes the amount of light that is emitted or reflected from a particular area, and indicates how bright the surface will appear from a particular angle of view. The uniformity describes how even the light is distributed over the surface and can be calculated by measuring illuminance in several points of a surface. In addition to measures of the electric lighting, road surface evenness is relevant since it is related to the perceived comfort of in particular cyclists (Landis et al. 1997; Lee & Moudon 2008). Path widths, important for interactions and actual and perceived safety of road users, are also considered (Veroude et al., 2022; Egeskog et al., 2023).

OBEA is described as “person-centred” and “subjective” as it relies on people’s tools such as questionnaires in which people express perceptions, observations and impressions, i.e. it employs human perception to define the environmental quality (Moser & Uzzell, 2003; Bonaituo et al., 2006; Fornara et al., 2010). OBEAs relevant for the present context refers people’s perceptions of walk and cycle paths (e.g. surface, upkeep, lighting) and the surroundings (e.g. aesthetics and complexity, presence of greenery), are further described in the development of the theoretical conceptual model below.The two assessment approaches should therefore be regarded as complementary as it is important to also gain people’s more holistic understanding, embedding interacting social processes within the context of their places (Uzzell et al., 2002).

Daylight and electric light conditions

So far, daylight and dark conditions seem to be considered separately in research on walking and cycling. Researchers in transport planning, geography, public health, and psychology have primarily been concerned with urban form, use, and experience of walking and cycling, without taking any great interest in how the perception of a setting transforms when the user travels at different speeds, or when it is getting dark (e.g. Brownson et al., 2009; Christiansen et al., 2016). Lighting researchers have focused more on dark conditions and the role of electric lighting for pedestrians, and more recently, cyclists (Fotios & Castleton, 2016; Fotios & Castleton, 2015; Fotios et al., 2005; Fotios et al., 2019). A few studies have reflected on how electric light is experienced as interacting with the surroundings (Nikunen & Korpela, 2012; Nasar & Bokharaei, 2017; Rahm, et al., 2021). Still the literature lacks a systematic and integrated approach for addressing people's environmental experiences walking or cycling along the same (shared) path, and how their experiences may differ between daylight and electric light conditions.

Observing pedestrian and cyclist behaviour

The study of pedestrian and cyclist behaviour have examined route preferences and self-reported travel times under different lighting conditions (Fotios & Robbins, 2022), compared observed pedestrian/cyclist flows between daylight and electric light conditions in field (Rahm & Johansson, 2021; Uttley et al., 2020; Uttley et al., 2021), and assessed walking time in a controlled laboratory setting using different electric lighting conditions (Pedersen & Johansson, 2016). Füssl & Haupt (2017) used a qualitative approach to gain a more nuanced understanding of cyclists' behaviour in terms of cyclists' identity and related interaction strategies. Current approaches provide limited information on how pedestrians and bicyclists behave *while* walking or cycling. Methodological triangulation could be useful for addressing this issue. Mattsson et al. (2020) combined measurements of path conditions, self-reports on the walking experience and observed the movements of visually impaired pedestrians using a walk-along approach on site. This approach allowed for detailed information about the pedestrians' placement, but was also a very time-consuming method. Nevertheless, such detailed behavioural information could be useful in evaluations of electric lighting for pedestrians.

In urban traffic studies, observation is a common method for behaviour analysis, and this is usually done using video recording analysis. This approach has various advantages compared to the use of field observations (Laureshyn, 2010) as precise microscopic data (on various measurable parameters) can be obtained from video footage (Laureshyn et al., 2009; Gavriilidou et al., 2019; Hussein & Sayed, 2017; Alsaleh & Sayed, 2020;). In previous behavioural studies, commonly examined characteristics include the placement and speed profiles of road users. A number of studies have confirmed that placement and speed may reflect changes in behaviour in response to the environment (Fisher & Nasar, 1992; Franěk, 2012).

In our earlier work (Johansson et al., 2020), we proposed the use of a video-based method (VAMP) to analyse pedestrians' microscopic movements by using their lateral position and speed. Using this method to assess pedestrian behaviour in a shared walk/cycle path we found that when increasing the illuminance at the path the pedestrians tended to walk closer to the white line to the adjacent cycle path as the surrounding grass were perceived as relatively darker, thereby increasing the risk of collision. This study was strictly based on an assessment of the movements of a limited number of participants recruited for the study, and it is unclear whether such a sample would be representative of pedestrians in general. Overall, there is a need for effective methods to assess the impact of lighting on cyclists and pedestrian behaviour (CIE, 2019; Uttley et al., 2021;).

Project aims and goals

The overarching aim of the BELYSA-project was to improve the quality of travel for pedestrians and cyclists during dark hours. The specific goals were to:

• Develop an objective quality-of-trip measuring method for pedestrian and bicycle traffic with focus on micro-level environmental factors.

• Implement improved lighting solutions at experimental sites and evaluate the combined effect of the lighting and other important micro-level environmental factors on pedestrians' and cyclists' experiences and behaviour.

• Provide recommendations for design, maintenance and lighting of pedestrian and cycling infrastructure.

Funding, research team and project organisation.

The BELYSA-project was funded by the Swedish Energy Agency grant Dnr: 48141-1, during the period 2019-2022, and due to the Covid-19 pandemic extended to 2024. The research team was multidisciplinary and included researchers from Environmental Psychology, Department of Architecture and Built Environment, Lund University, Transport and Roads Division, Department of Technology and Society, Lund University and Infrastructure Maintenance at the Swedish Road and Transport Institute (VTI).

The research project was headed by Maria Johansson, professor in environmental psychology and Johan Rahm, senior associate lecturer in environmental psychology, Department of Architecture and Built Environment, Lund University. The environmental psychology team had the main responsibility for the observer-based environmental assessments. Maria Johansson has served as PI and had a lead in conceptualisation, funding acquisition, methodology, analyses, project administration and writing. Johan Rahm has served as co-PI in all parts, and had major responsibility for data collection and analyses of observer-based environmental assessments, been involved in conceptualisation, funding acquisition, methodology, project administration and writing.

The Transport and Roads Division managed video data collections and video data analyses. Senior lecturer in traffic safety, Aliaksei Laureshyn, has been involved in conceptualization, funding acquisition, methodology, and project administration. Video data collection was carried out by Oksana Yastremska-Kravchenko, a PhD student in traffic safety, Carl Johansson, a postdoctoral researcher in traffic safety, and Samir Hammad, a project assistant. Video data processing was performed by Oksana Yastremska-Kravchenko, with assistance from Kevin Gildea, a postdoctoral researcher in traffic safety, and Lisa Hiselius, a project assistant. Video data analyses were mainly conducted by Oksana Yastremska-Kravchenko.

The VTI part in this research project has been to perform and analyse TEA measurements and to develop measuring equipment and methods. Senior research leader Anna Niska has been involved in conceptualisation, funding acquisition, methodology, project administration and writing and has also conducted some of the measurements and data analyses. Measurements have also been performed by analyst Jenny Eriksson, research engineer Mattias Thunberg and PhD student Martin Larsson. Data analyses have mainly been conducted by research engineer Peter Andrén and Jenny Eriksson. Senior research leader Leif Sjögren has been involved in conceptualisation, funding acquisition, methodology and some of the measurements. Research engineers Harry Sörensen and Claudia Bratu and measurement engineer Linda Corper as well as tecnicians at the measurement and technology department at VTI have been involved in the development of the Bicycle Measurement Trailer and its associated software.

Lund Municipality and Linköping Municipality participated in discussions on planning, management and design of walk and cycle paths, together with the research team selected the paths for the case studies. The municipalities based on the baseline assessment decided on the interventions to introduce and fully funded and implemented the interventions.

The project was outlined in five integrated and partly overlapping work-packages (WPs) with WPs 1, 2 and 4 covering the major parts of the research.

WP1 was based on previous research on environmental experiences and behaviour. WP1 served to develop and apply a multidisciplinary theoretical framework to identify and assess micro-level environmental factors.

WP2 specifically referred to the technical development and establishment of a protocol for technical environmental assessments from cyclist- and pedestrian-perspectives in both daylight and electric lighting conditions.

WP3 consisted of development and implementation of interventions that potentially would improve conditions for pedestrians and cyclists at the study sites

WP4 evaluated the implemented interventions on-site following the theoretical framework (WP1) as well as the procedures and protocols used for the baseline measures collected in WP2.

WP5 aimed at further analysing, synthesising and reporting the results from earlier WPs and to translate these results into current regulations and recommendations for design and maintenance of walking and cycling infrastructure.

The multidisciplinary theoretical conceptual model

In accordance with WP1 the first phase of the project was dedicated to develop shared perspectives and to develop a theoretical conceptual model that integrate previous research on environmental features and walking and cycling in daylight and electric light conditions. This first step was deemed necessary to set-up a systematic approach for choice of measures, and assessments in the evaluations of interventions.

In BELYSA environmental psychology theory on human-environment interaction was used to understand pedestrian and cyclists' environmental experiences and behaviour. A key feature of such theory is that no perfect association between measured micro-level environmental factors and walking and cycling can be expected, rather this involves human psychological processes requiring a holistic approach (Küller, 1991; Alfonzo, 2005; Nasar 2008). Our previous research on urban walking carried out during daylight conditions show for example that both perceived environmental qualities and affective experiences are relevant to walking intentions (Ferreira et al., 2016; Johansson et al., 2016). Previous studies also suggest that the understanding of behavioural outcomes in parallel would need to consider the role of experiences of micro-level environmental factors in combination with social psychological factors, such as attitudes (e.g. Mattsson 2015), as for example outlined by Theory of Planned Behaviour (TPB, Ajzen, 1991; Fishbein & Ajzen, 2010), and such integrated frameworks may also serve to predict how outdoor environments facilitates walking and cycling (Webb et al., 2018; Wilhoit, 2018).

The conceptual model developed is based on theories and previous findings from the field of environmental psychology, especially drawing on Brunswik's (1952) " lens model" as a framework to illustrate the probabilistic nature of the perceptual processes underlying behaviour (Rahm et al., 2024a). The model consists of four steps further described below. An underlying assumption is that all aspects of the individual responses partly depend on individual characteristics and prior experiences (Johansson et al., 2016). This includes sociodemographic factors (e.g. age, gender, level of education) as well as previous experiences of being in similar environments to the path's location.

The conceptual model proposed (Figure 1) draws on Brunswik's (1952) lens model. The conceptual model also aligns with the view of Johansson et al. (2016) on how different aspects of the physical environment influence the walking experience and walking intentions, but adds to it in three ways. Firstly, the conceptual model further emphasises the perceptual processes of pedestrians and cyclists. Secondly, the model considers a wider range of perceived design qualities, and thirdly, the conceptual model integrates attitudinal theory to describe aspects of behavioural intention in greater detail.

The first step of the conceptual model incorporates the physical environment itself, in this case a pedestrian/cycle path during daytime and after dark, and the perceptual processes of the pedestrian/cyclist. In Brunswik's (1952) lens model the individual-environment system serve as the fundamental unit of analysis (Vicente, 2003), and differentiates between distal stimuli (objective descriptors of the setting) and proximal stimuli (imperfect sensory information). Here, we adopt the concepts of distal and perceived stimuli as a means for differentiating between characteristics of the environment measured by technical equipment (TEA) and characteristics perceived by the participants (OBEA). Thereby accounting for both types in the proposed model.

Applied to the present case, distal variables as measured by technical environmental assessment were chosen to represent important stimuli in the environment of pedestrians/cyclists during their trip that can be measured by technical environmental assessment: the width and evenness of the path (Thigpen et al., 2015), the composition of the vegetation bordering the path (Peet et al., 1998), and variables related to electric lighting (horizontal illuminance and correlated colour temperature (CEN, 2003). Perceived variables as measured by observer-based environmental assessment instruments represented perceived urban design qualities (Johansson, et al., 2016), perceived surface quality, traffic environment, social atmosphere, outdoor lighting quality (Johansson et al., 2014), and levels of prospect and escape possibilities (Nasar et al., 1993).

The perceived stimuli act together, similar to the collative properties of visual stimuli (Cupchik & Berlyne, 1979), and thereby form the perceptual basis for higher order conceptual environmental appraisals in which perceptions of specific stimuli are integrated (Johansson et al., 2019). Johansson et al. (2024) further developed the conceptual environmental appraisals, especially for walking along urban forest paths – amongst others proposing the role of complementary theories on restorative qualities. In the present context the various perceived variables serve as the basis for conceptual environmental appraisal: perceived safety (Haans & de Kort, 2012; Boomsma & Steg, 2014; Rahm et al., 2021), visual accessibility (Johansson et al., 2011; Rahm & Johansson, 2021), and restorative potential (Nikunen & Korpela, 2012).

The third step of the model accounts for how environmental appraisals translate into affective responses and microscopic movements. Mehrabian and Russell (1974) proposed that people's affective responses to the built environment consist of the dimensions valence (unpleasant-pleasant) and arousal (passive-active). These affective experiences seem to mediate between the perceived qualities of the environment and behavioural intentions (Johansson, et al., 2016). People tend to respond to an environmental setting by making minor adaptations to their movement micro-level behaviours in terms of walking speed and placement on the path (Johansson et al., 2020).

The final step focuses on the behavioural intentions of pedestrians and cyclists. The cumulative affective experiences during the walk/cycle trip are likely to influence the intention to walk/cycle a similar path in the near future (Alfonzo, 2005; Johansson et al., 2016). We also integrate the theory of planned behaviour (TPB) (Ajzen, 1991) to account for the complexity associated with predicting future behaviour. TPB, suggests that three factors: the individual's attitude towards conducting the behaviour, the perceived social pressure to perform or not perform the behaviour (subjective norm), and the perceived ease/difficulty of performing the behaviour (perceived behavioural control) will influence the intention to walk/cycle (Ajzen, 1991), i.e. the self-reported likelihood of choosing/avoiding a similar path in the near future (Johansson, et al., 2016).

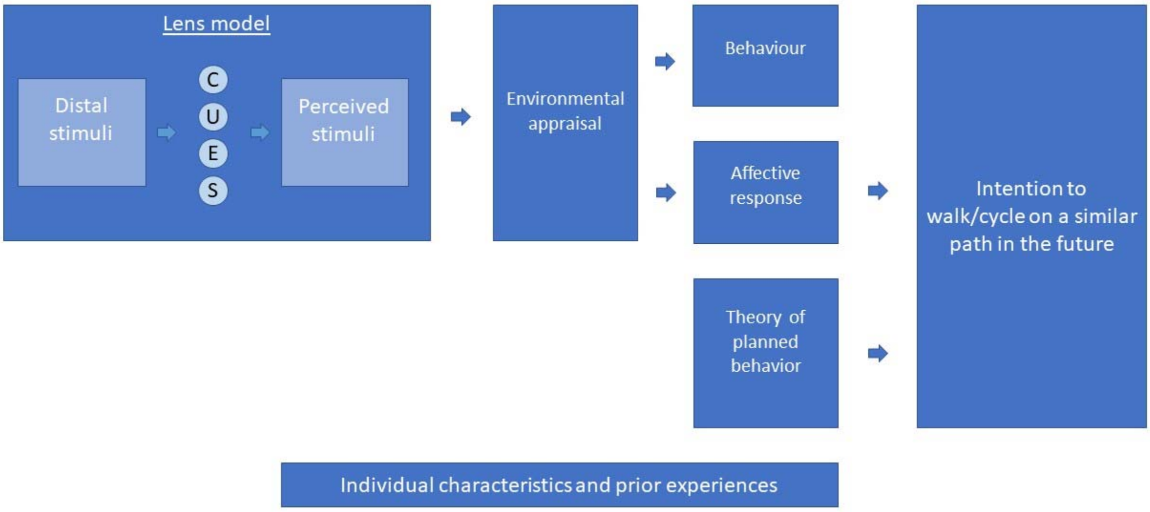

Figure 1. Theoretical conceptual model of the physical environment's influence on the walking/cycling experience and behavioural intentions to use a similar path in the near future (Rahm et al., 2024a).

Method

Research design and choice of paths in Lund and Linköping

The empirical studies were conducted in collaboration with the municipalities of Lund and Linköping. The settings – our empirical cases the walking/cycling paths were selected together with the municipality traffic planners and lighting officers.

The shared criteria developed referred to

- paths partly used for walking/cycling communting between the city outskirts and the city centre,

- the path should be shared between pedestrians and cyclists,
- the path should be relevant for the municipality to up-date the electric lighting within the project time taking into consideration the project baseline results.

The project main study was designed as a field experiment and after baseline assessments involved the introduction of on-site environmental interventions at two locations, Lund and Linköping. The project period included the years of the Covid-19 pandemic 2020-2021. This jeoparized the possibilities for strictly following the planning outlined with the muncipalities. After baseline assessments in 2019, in Lund one major intervention was introduced, whereas in Linköping we could hold on to a stepwise approach, first changing the layout and surface of the path, and then replacing the electric lighting.

The research was also cross-sectional comparing pedestrian- and cyclist environmental assesments and behaviour in the same settings during daylight and electric lighting conditions (Table 1).

In each one of the measurement occasions, baseline – study 1, post-test-study 2, and post-test-study 3 the paths were investigated by technical environmental assessments, observer-based environmental assessments and behavioural observations both among pedestrians and cyclists, and during daylight and electric light conditions. Altogether, five data collection periods, were conducted.

In Linköping, three data collections were performed, capturing the changes in path pavement (including the appearance of a middle line and road marking symbols) between the baseline and second data collection, and changes in electrical lighting application between the second and third data collection periods.

In Lund, two data collections were conducted, with the pavement, vegetation, and the electrical lighting application being changed between them. Additional field data was collected at the same sites, but without relying on invited participants.

Energimyndigheten

Table 1. Overview of the research design

Location	Baseline Study 1	Intervention 1	Post-test Study 2	Intervention 2	Post-test Study 3
Linköping	Measures: TEA OBEA Behavioural observation Period: Oct-Nov 2019 March 2020*	Environment: New asphalt Traffic separation	Measures: TEA OBEA Behavioural observation Period: November 2021	Light: Replaced lighting	Measure: TEA OBEA Behavioural observation Period: November 2022
Lund	Measures: TEA OBEA Behavioural observation Period: Jan-Feb 2020	Environment & Light: New asphalt Reduced vegetation Replaced lighting	Measures: TEA OBEA Behavioural observation Period: Feb-Mar 2022	-	-

* March 2-5 (interrupted due to Covid)

Study site and interventions in Linköping

The study site in Linköping was a combined cycle and pedestrian path (175 metres long, 3.2 to 4.3 metres wide) located in the outskirts of the city centre (Figure. 1b). On the left-hand side of the path there was a road, and on the right-hand side were residential multi-storey buildings. The path surface was asphalt. The luminaire was a Philips SGS 203, with a high pressure sodium light source (Power: 100 W, Correlated color temperature, CCT: 2000 K) The luminaires were mounted on 7-metre-high lampposts , approximately 1,5 meters from the edge of the path, placed 30 metres apart.

Intervention 1: In the first step the path was widened to 3,9 to 4.6 metres, and there was new asphalt. Cyclists and pedestrians were separated by a white line and road marking symbols (as shown above in Figure 1). The cycle path then had a width of 2.7 to 3.0 metres and the footpath a width of 1.2 to 1.6 metres.

In intervention 2: In the second step the electric lighting was changed. The original lamp posts were reused for the new luminaires, which were installed at the same locations. The new luminaire was a Schreder/Teceo 1, with a LED light source (Power: 44 W, CCT: 4000 K).

Figure 1. The path in Linköping before (to the left) and after intervention 1 (to the right).

Study site and interventions in Lund

The study site in Lund was a segregated cycle and pedestrian path (245 metres long, 4.05 to 5.3 metres wide; separated by a white line) located in the city centre (Figure. 2). The cycle path was one-directional (with cycling towards the city center on the north side of the roadway and cycling in the other direction on the south side of the roadway), but in practice often used as bi-directional. On the left-hand side of the path was a road, and on the right-hand side trees and bushes bordered the path. The path surface was asphalt and was lit by Järnkonst 7455 with a high pressure sodium light source (power: 100 W, CCT: 2000 K), placed 30 meters apart and were mounted on catenaries nine meters above the ground, approximately six meters from the edge of the path.

Intervention 1: In Lund the surfacing was changed at the same time as the electric lighting and the greeneray was trimmed to increase sight and decrease shading of the path. The new luminaires (Philips BSS562 with LED light source, Power: 33.5 W, CCT: 3000), two on each catenary, were installed at the same locations, at a height of 9 meters but at a distance of three meters from the edge of the path.

The paths were extensively measured and described at baseline and after each intervention. How this was done and the results are further described under the section methodological developments.

Figure 2. The path in Lund before (to the left) and after intervention 1 (to the right).

Figure 3. Baseline sites studied under conditions of daylight and electric lighting. Linköping, (to the left) and Lund (to the right) (Yastremska-Kravchenko et al., 2024b)

Figure 4. Interventions in Linköping. Intervention 1 (to the left) and Intervention 2 (to othe right) (Yastremska-Kravchenko et al., 2024a)

Figure 5. Interventions in Lund (Yastremska-Kravchenko et al., 2024a)

Study participants

In total 600 study participants were included in the research project. Most of the participants were part of the experimental studies. They were students recruited via open advertisments at Linköping (n = 255) or Lund universities (n = 169), aged between 18-35 years 54% female and 46% male with self-reported normal eye-sight. For further details please refer to Table 2.

In addition pedestrians and cyclists were recruited on site during their regular trips and asked to respond to a few short questions (Linköping n = 94, and Lund n = 82). This sample was more varied in terms of socio-demographics. Their aged ranged from 18 to 89 years (mean age 46 years), and 55% were female. These sample was also to a larger degree employed (total sample: 59%; Linköping: 63%; Lund: 53%), students (total sample: 22%; Linköping:11%; Lund: 35%), or had another occupational status, e.g retired or unemployed (total sample: 19%;

Linköping: 26%; Lund: 12%). These participants forms the naturalistic sample for the observer-based environmental assessments.

Table 2. Overview of participants in data collection for experimental studies.

Location	**Baseline* Study 1**	**Post-test* Study 2***	**Post-test* Study 3**
Linköping: Empirical study	38 (19, 19); 41 (21, 20) Mean age 24 years	43 (23, 20); 45 (23, 22) Mean age 22 years	46 (23, 23); 42 (23, 19) Mean age 23 years
Linköping: Naturalistic	*49 (23, 26); 44 (17, 27) Mean age 51 years*	*43; 41*	
Lund: Empirical study	41 (26, 15); 44 (24, 20) Mean age 23 years	43 (23, 20); 42 (21, 21) Mean age 24 years	-
Lund: Naturalistic	*42 (21, 21); 40 (19, 21) Mean age 40 years*		-

*Number of participants. Day (Walk, Cycle) ; Night (Walk, Cycle)

The structured walks

The data collections for observer-based environmental assessments (OBEAs) were designed as structured walks (Johansson et al., 2016; Johansson et al., 2019; Rahm & Johansson, 2021). The idea of the structured walk is that study participants' experiences of a setting, in our case the walk/cycle paths are assessed on-site, providing high validity of the assessments.

The participants arrived at the test sites in approximate groups of five. They were informed about the purpose of the study, how their personal information would be treated, and about their right to withdraw from the study without providing an explanation, before signing an informed consent form.

Participants walked to the starting point together and completed the first part of the questionnaire. When this was completed, the participants were randomly allocated to walk or cycle, and individually walked/cycled along the path to the end point, where they completed the second part of the questionnaire. These walks were as far as possible video recorded by means of drones as further described. Not all walks could be recorded due to flying restrictions imposed with short notice by the nearby airport or unfavourable weather condition. The group then walked back to the starting point together, where they completed the third part of the questionnaire.

The procedure complied in all aspects with ethical rules for psychological research but, as the study did not address sensitive personal sensitive information as defined by the Swedish Ethical Review Authority, no formal ethical approval was needed.

Data collections took place during a time-frame characterised by reduced daylight hours during the Swedish autumn and wintertime from October to March. The temperatures ranged from -1° to 14° Celsius and there was no precipitation during most occasions (ranging from 84% to 100% of the occasions for each condition). However, the surface of the path was still wet during approximately half of the occasions. During the baseline measurements there were no leaves on the trees, but during the second and third data collection in Linköping, there were still some leaves left on the tree branches.

Video data

All video data were gathered using drones as a tool for collection, rather than ground-based cameras. Utilizing drones for this study offers several advantages over traditional cameras: (i) it nearly eliminates mounting and power supply issues, although careful planning is necessary due to limited filming time per flight due to battery capacity; (ii) a single camera view can cover a large area of interest; and (iii) the drone's perspective and relatively distant position from the observed subjects (the officially permitted flight height limit is 120 meters). Indeed, this distance makes it impossible to identify individual persons, thereby eliminating the need for cumbersome procedures related to handling personal data as per the EU GDPR (GDPR, 2016), which is also a part of Swedish law. Consequently, drone-based data collection does not require consent from individuals being filmed, facilitating observations of behaviour in a naturalistic setting.

Video data were captured during daylight and electric lighting, each covering approximately 15 working days at each location for every data collection period (Table 3). The observed sections, recorded by cameras positioned at a height of 120 meters, spanned approximately 150 meters in length.

Table 3. Comprehensive overview of data collection process for drone videos

Location	Study	number of drone videos		Lighting condition DL/EL	Time
		Experiment	Naturalistic		
Linköping	1	20	14	DL	08.00-10.00
				EL	17.00-20.00
	2	18	25	DL	14.00-16.00
				EL	17.30-20.00
	3	17	20	DL	14.00-17.00
				EL	18.45-21.00
Lund	1	19	16	DL	14.00-16.00
				EL	18.30-21.00
	2	26	32	DL	13.00-16.00
				EL	17.30-20.00

* DL – daylight, EL Electrical lighting

Two types of empirical data were collected: (i) video recordings of invited participants for the experiment study, constituting invited/aware sample data, and (ii) naturalistic data of undisturbed traffic in real-life conditions, constituting unaware sample data. In total, over 200 drone flights were conducted, with each flight having a limited duration; in our case, the battery lasted for 25 minutes, allowing approximately 20 minutes of filming, including approximately 5 minutes for take-off and landing.

Methodological developments

Methodological developments 1: Distal variables measured by TEA

The first part of the methodological developments refer to the selection of distal variables of relevance to describe walk and cycle paths from a user perspective and to reliable measure the variables in field at a levels adapted to pedestrian and cyclist needs. The distal variables included road lighting (photometric properties): luminance [cd/m^2] and illuminance [lx], road/track width and to some extent (due to technical failures) road surface texture and evenness. Track width was measured using a folding rule or measuring tape. The total width as well as the width of footpath and cycle path respectively was noted, in the cases of separate paths. The length between lampposts and the total length of the test sections was measured using a measuring wheel (a Trumeter).

Road lighting performance

The illuminance is the most relevant feature considering the lighting interventions, and thus the main focus in this report. There are multiple functional requirements regulating road lighting performance such as luminance [cd/m^2], illuminance [lx], glare and uniformity, and there is a European standard adopted by Sweden (SIS) that specifies measurement conditions and procedures for measuring different quality parameters (SS EN 13201-3:2016). Illuminance describes the ability of lighting to illuminate objects and is related to the "brightness" perceived by road users. Luminance describes the amount of light that is emitted or reflected from a particular area, and indicates how bright the surface will appear from a particular angle of view.

The horizontal illuminance on the paths under electric lighting was measured with a Konica Minolta T-10 Illuminance meter both manually (static measurement) and automatically (dynamic measurement), with the illuminance meter mounted on a bicycle measurement trailer, BMT (see further description below). Manual measurements were performed at ground level according to the Swedish and European Standard for measuring road lighting performance (SS EN 13201-3:2016). Specifically, a measurement was conducted under each lamppost and in a 3x10 grid of points between the lampposts to capture the brightest and darkest areas of the test sections. This process resulted in illuminance measures being performed every 3 meters in these areas and at three points along the width for each of these positions (at a distance of d1 = 0.53, d2 = 1.60 and d3 = 2.67 meters from the edge of the curbstone between the paths and the adjacent roadway in Linköping (Figure 1), and at a distance of d1 = 0.68, d2 = 2.03 and d3 = 3.38, respectively, in Lund (Figure 2). According to the standard, the average illuminance ($\bar{E}$) should be displayed, calculated as the arithmetic mean of the illuminances at the grid points. To illustrate the variation of illuminance over the studied sections, the whole length of the studied areas was also measured with the

BMT resulting in an illuminance measure every 5 millimetres – usually in the middle of the cycle path (corresponding to the middle manual measure). Luminance under electric lighting was measured manually with a Konica Minolta LS100 on the lightest and darkest spots of the paths.

The bicycle measurement trailer

The Bicycle Measurement Trailer (BMT) is a prototype developed at VTI to facilitate condition assessment on cycle paths. With the BMT it is possible to perform dynamic and continues measurements of illuminance along the route, surface texture and evenness at normal cycling speeds, without interfering with the traffic or preventing other road users from accessing the cycle path. Traditional systems with laser profilometers for condition assessment of roads are less suitable for cycle paths due to their size (Larsson et al., 2023) and required minimum speed of the measuring vehicle (Sayers & Karamihas, 1996). The BMT consists of a pedelec with an attached trailer, equipped with measuring and data acquisition devices, as shown in Figure 6. The system is controlled via a laptop computer and powered by a car battery installed in the trailer. A specially developed software is used for data collection and processing.

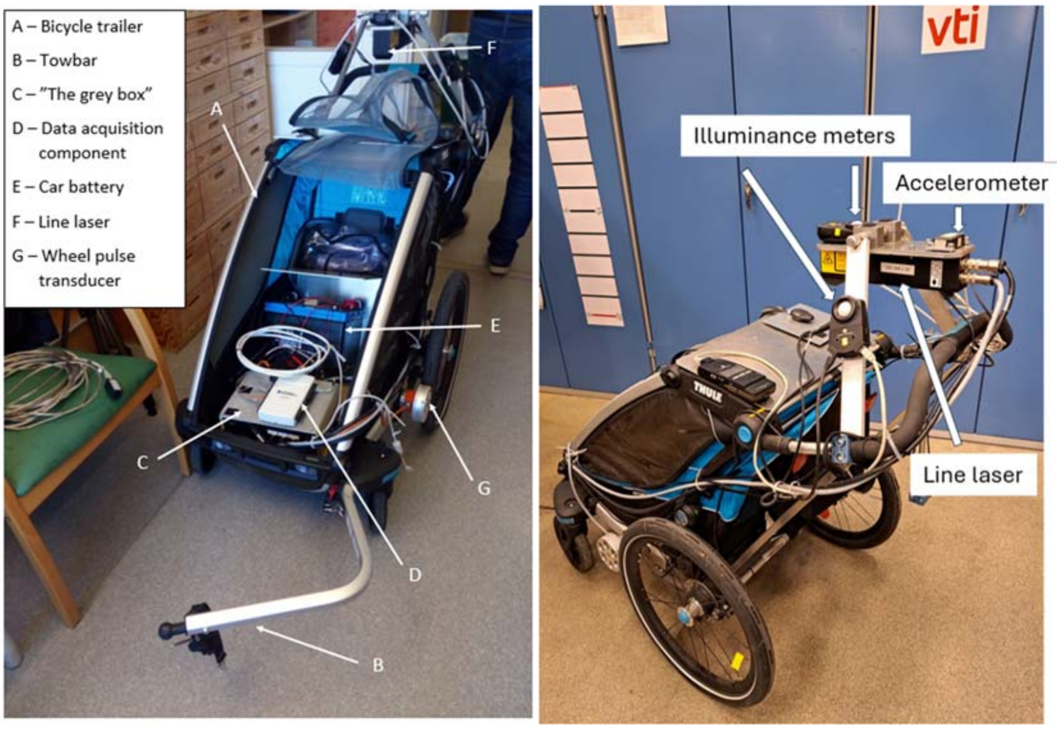

Figure 6. The VTI Bicycle Measurement Trailer (BMT). To the left: inside of the BMT, with the components that make up the system. To the right: The mounting of the illuminance meters.

Illuminance meters, a Gocator 2375 line-laser and an accelerometer are mounted on a specially constructed frame attached to the handlebar of the trailer, as seen in Figure 6. In the road lighting measurements performed in this project, the BMT was equipped with three illuminance meters, one on top of the frame (1.09 meters from the ground) and one on each side of the frame. The idea was to catch illuminance observed at the sides of the path. However, it was concluded from the results that the illuminance meters on the sides often gave invalid values, especially the one on the outer side away from the lampposts, due to shading. Therefore, only the data from the top mounted illuminance meter was analysed and presented in the results.

The development of the BMT has been on-going throughout the BELYSA-project, within a process of trial and error. Adjustments of the components as well as the software for data collection and processing has been done repeatedly, and there have been some technical difficulties impairing the data collection with the BMT. Therefore, data from the BMT should only be considered as a bonus material and for comparing the environmental items between the different occasions of participant studies, we have had to relate on the standard measurements performed manually.

One conclusion from the measurements performed with the BMT is that the system is somewhat sensitive to low temperatures and moist conditions. This was in particular true for the laser measurements, and on several occasions, we had to re-do these measurements. We therefore adjusted the measuring procedure along the progress of the project. For example, in the beginning, we performed illuminance and road surface measurements simultaneously, but in order to attain more stable and reliable results, we later on decided to measure the different items at separate occasions. The road surface measurements were then performed during daytime with greater likelihood of dry conditions and higher temperatures, and only illuminance was measured during nighttime under electric light conditions.

Road surface condition

With the Gocator line-laser and the accelerometer mounted on the BMT, it is possible to measure the road surface evenness and texture – parameters that are related to the comfort of cyclists. When riding over a surface, cyclists are subjected to vibrations in the bicycle caused by acceleration from the unevenness of the surface. These vibrations can be measured using accelerometers mounted on a bicycle, an approach that has been used in several studies trying to capture the effect on cyclists of surfaces with different roughness (Zang et al. 2018; Joo et al., 2015; Olieman et al. 2012; Hölzel et al. 2012; Giubilato & Petrone 2012; Yamanaka et al. 2013; Litzenberger et al. 2018; Bíl et al. 2015; Gao et al. 2018; Niska & Sjögren 2014). Depending on wavelength, the surface evenness is divided into different spectra/metrics: micro texture (<0.5 mm), macro texture (0.5 – 50 mm), e.g., protruding aggregates or cracks, and mega texture spectrum (50 – 500 mm), e.g., potholes and smaller bumps, and unevenness (0.5 – 5 m) such as larger bumps or settlements on restored pavement sections. Previous research suggests that it is unevenness with wavelengths ranging from about 5 mm up to 3 meters that will affect the comfort of cyclists (Niska et al. 2011). A method that can cover both the texture and unevenness is therefore of great importance for cycle path surfaces. Research in this field is still rather immature and there is yet no standard method for cycle path surfaces. Both standard measurement methods and metrics for roadways have been found to be inapplicable for cycle paths. In on-going research projects conducted at VTI we are developing measuring methods more suitable for cycle paths and are also trying to define metrics and limit values describing surface evenness that are related to the comfort of cyclists and could be used, for example, in contract performance control of newly built cycle path surfaces. The development of the BMT is one important component in the aspiration to achive this goal.

When performing road surface measurements with the BMT, the surface transvers profile (appr. 500 mm width) behind the bicycle is scanned by the line laser as the bicycle advances. The cycle path measured is given a coordinate system, whereby the x-axis denotes the width, the y-axis denotes the longitudinal direction, and the z-axis denotes the vertical position of the cycle path surface in the corresponding x-y coordinate. The vertical position, i.e. the height of each data point on each scanned transverse profile is determined by the reflected light of the laser. The maximum resolution with the current configuration of the BMT is 0.5 mm for x, 1.2 mm for y and 0.25 mm for z, and the maximum possible width of the transverse profile is 542 mm. Data from the accelerometer attached on top of the mount is used to extract the movements of the trailer in the analysis of the measured data.

Before the measurements, the surfaces of the sections were manually swept with a broom to get rid of any gravel, debris or other elements that could potentially influence the measurement. However, during the measurements in October and November it was difficult to completely clear the surface from wet leaves that had fallen from the trees. The test sections were then measured using a distance measuring wheel and marked out with road marking chalk. Reflective plates to trigger the start and stop points of the BMT measurements were laid out on top of these markings. The measuring process with the BMT, the data processing and analysis is further described in Larsson et al. (2023).

When performing the baseline study, the BMT was still under development and was too immature to be able to deliver reliable data. At the first measurements there was no accelerometer mounted on the BMT which made it impossible to calculate true evenness information. Instead, an RMS value for the transverse profiles measured with the laser has been calculated to illustrate the difference in evenness of the surfaces before and after interventions. The RMS value (Root Mean Square) is indicating the standard deviation from a "zero level", and thus shows how unevennesses in the surface deviates from this level, in this case mainly describing the texture of the surfaces. The analyses have been done in MATLAB.

In further studies using the BMT we have been able to describe the longitudinal profile from the measurements and hence describe the evenness of cycle path surfaces. We have also showed that the evenness measured with the BMT correlates with standard measuring devices (Larsson et al, 2023).

Energimyndigheten

Methodological developments 2: Perceived stimuli and conceptual environmental appraisal assessed by OBEA

The methodological development for the observer-based environmental assessments was to select and develop adequate questionnaire batteries referring to relevant perceived stimuli and conceptual environmental appraisals (see further Rahm et al., 2024a). In this process we relied on our previous research on pedestrian environmental experiences using structured walks in daylight (Johansson et al., 2016; Johansson et al., 2019) and electric light (Rahm et al., 2021).

During the structured walks the participants were asked to complete the questionnaire designed to correspond to the observer-based environmental assessments of the theoretical conceptual model. Assessments of a broad range of perceived stimuli (first step of the model), covered the perceived urban design qualities scale (Johansson et al., 2016), the perceived surface quality scale, the traffic environment scale, the social atmosphere scale and the perceived outdoor lighting quality scale (Johansson et al., 2014). Two items were used to capture the prospect and escape aspects, deemed to be important for the perceived safety appraisal, according to the prospect-refuge theory (Appleton, 1975; Nasar & Jones, 1997; Nasar et al., 1993). The participants were asked to conduct conceptual environmental appraisals (second step of the model), by rating perceived visual accessibility (Johansson et al., 2011), perceived safety (Blöbaum & Hunecke, 2005) and the restorative potential of the environment (perceived restoration scale (Hartig et al., 1997). In order to assess the affective responses (third step of the model) the participants were presented with the affect grid (Russell et al., 1989) both before and after walking/cycling the path. Participants also responded to two items for each construct from TPB (Ajzen, 1991), and two items were used for assessing behavioural intention (the fourth step of the conceptual model) (Table 4). Most of the scales showed satisfactory to high internal reliability at the baseline assessments (data aggregated for Linköping and Lund) >.70) and have been aggregated into indices (Table 4). Assessments of social atmosphere, and the TPB constructs (subjective norm and behavioural control) showed low reliabilities, most likely due to the limited number of items included to limit the length of the questionnaire. As for the social atmosphere scale, the items have been treated separately in the analyses, whereas for TPB considering that this is a well established instrument items have been analysed as indices.

Table 4. Overview of scales and items used in the questionnaire. Reversed items in italic.

Concept	Items	Response scale	Internal reliability - baseline
Perceived stimuli			
Perceived urban design qualities scale	Fifteen statements addressing three overarching categories: <u>Complexity and aesthetic quality</u> There are a lot of interesting things to look at; The environment is varied; The buildings fit well together; *The environment is monotonous*; The environment is pleasant; The buildings are noticeable. <u>Upkeep and Order</u> *The environment is disordely The environment is untidy*; The environment is attractive and tidy; *The environment is run down*. <u>Well-maintained greenery</u> The greenery is attractive; The greenery is varied and diverse; The environment is green and leafy.	5-point Likert scale (1=no, certainly not; and 5=yes, certainly)	α=.77 α=.74 α=.79
Perceived surface quality scale	The surface is smooth; *There are irregularities*; *The surface is coarse*; There are cracks or potholes.		α=.70
Traffic environment scale	The environment is quiet; The air is free from exhaust; *There is a lot of car traffic*; *The cars are driving at high speed*.		α=.73
Social atmosphere scale	*There were conflicts between road-users*; *I experienced crowding*; Other road-users were considerate. Other road-users seemed friendly.		α=.56
Perceived outdoor lighting quality scale	Ten word pairs addressing two overarching categories: <u>Perceived strength quality, PSQ</u> Subdued-brilliant; strong-weak; dark-light; unfocused-focused; clear-drab. <u>Perceived comfort quality, PCQ</u> Hard-soft; warm-cool; glaring- shaded; natural-unnatural, mild-sharp.	7-point semantic differential scale	α=.68 α=.62
Prospect	I have good overview of the surroundings along the path.	5-point Likert scale (1=no, certainly not; and 5=yes, certainly)	
Escape	I could easily escape the path in the event of danger.		

Table 4 continued.

Conceptual environmental appraisals			
Perceived visual accessibility	I could have detected an object on the ground; I could have read street signs; I could have recognised people's faces; I could have detected cracks and irregularities in the path; In general, I could see well.	5-point Likert scale (1=no, certainly not; and 5=yes, certainly)	α=.87
Perceived safety	*I would walk/cycle a detour to avoid the path*; *I felt uneasy along the path*; *I would hurry to get away from the path*; *I felt that this path was unpleasant*; I would consider walking/cycling alone along the path.		α=.86
Perceived restoration scale	There is much to explore and discover here; Spending time here gives me a break from my day-to-day routine; It is a place to get away from the things that usually demand my attention; This place is fascinating; I like this environment.		α=.74
Affective response			
Valence	Two-dimensional grid consisting of 5x5 squares	A score of 1-5 on each axis	-
Arousal			-
Theory of Planned Behaviour			
Attitude towards w/c	I think it is good to walk/cycle on this kind of path; I think it is pleasurable to walk on this kind of path.	5-point Likert scale (1=no, certainly not; and 5=yes, certainly)	r=.82
Subjective norm	Most people who are important to me think it is good to walk/cycle on this kind of path; Most people like me walk/cycle this kind of path.		r=.55
Perceived behavioural control	I am confident that I could regularly walk/cycle on this kind of path; It would be difficult for me to walk/cycle on this kind of path more frequently.		r=.54
Behavioural intention			
Choose path	Would you specifically choose this path?	5-point Likert scale (1=no, certainly not; and 5=yes, certainly)	
Avoid path	Would you specifically avoid this path?		

To explore the validity of the study participants invited to the experimental study assessments were compared with the naturalistic sample. Mann-Whitney U tests were conducted for the measures that were included both in the short and in the full questionnaire (Perceived surface quality, Perceived outdoor lighting quality, and items from Visual accessibility and Perceived safety). The only significant difference between participants in the experimental study and the naturalistic sample was for cyclists in Linköping during daylight, where the naturalistic sample rated the perceived surface quality as significantly higher than did the participants ($p = .031$, $r = .32$; $m_{Passersby}=3.77$, $m_{participants} = 3.38$).

Methodological developments 3: Behavioural observation by drones

Video-recorded data treatment

Before generating trajectories of the microscopic behaviour of bicyclists and pedestrians for further analysis, each video recording underwent several processing steps:

- Video stabilization: This step eliminates unwanted camera shakes caused by wind.
- Brightness adjustment: Applied only when necessary for recordings under electric lighting, this process alters the image's brightness to enhance the visibility of road users.
- Video calibration: This involves constructing a model that correlates the camera image with 3D world coordinates.

For the first two steps, we used video editing software, DaVinci Resolve16 (Saccone & Scoppettuolo, 2020). The third step was conducted using T-Calibration software (T-Analyst, 2018), which employs the Tsai camera calibration model (Tsai, 1986). The parameters for this calibration model were estimated using a set of calibration points with known coordinates in both the image (x_i, y_i) and the 3D-world system (X_w, Y_w, Z_w). These coordinates were measured using a Leica Builder R200M total station. The calibration points were marked along both edges of the shared-use paths at intervals of approximately 4 meters (Figure 7).

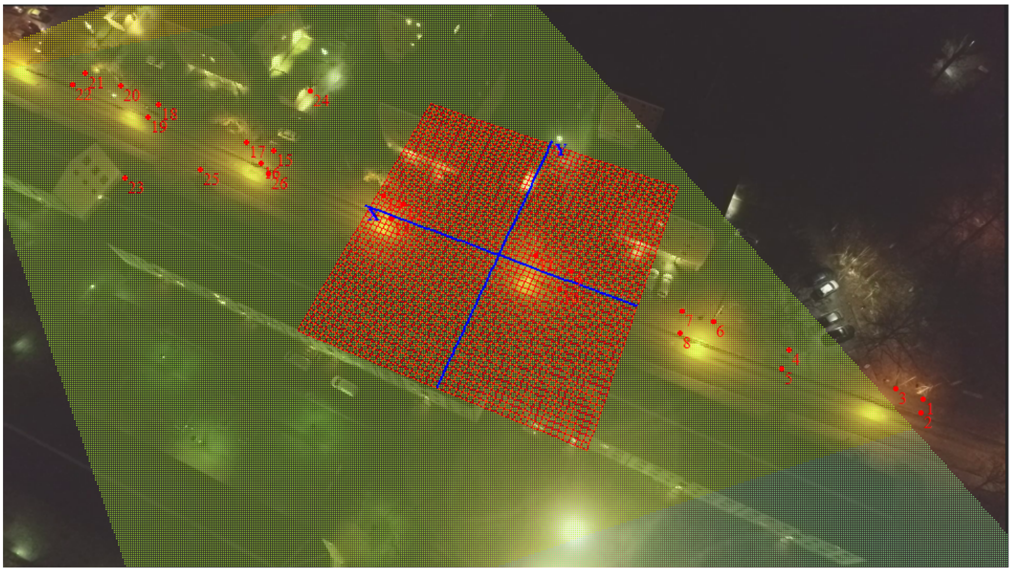

Figure 7. Camera calibration and levels of accuracy. Red dots show the position of calibration points (Yastremska-Kravchenko et al., 2024b)

Trajectory data

Once all processing steps were completed, pedestrians and cyclists could be tracked along the path. Trajectories were generated and extracted using a semi-automated video analysis tool, T-Analyst (refer to Figure 8). (T-Analyst, 2018). For further details please refer to (Yastremska-Kravchenko et al., 2024b)

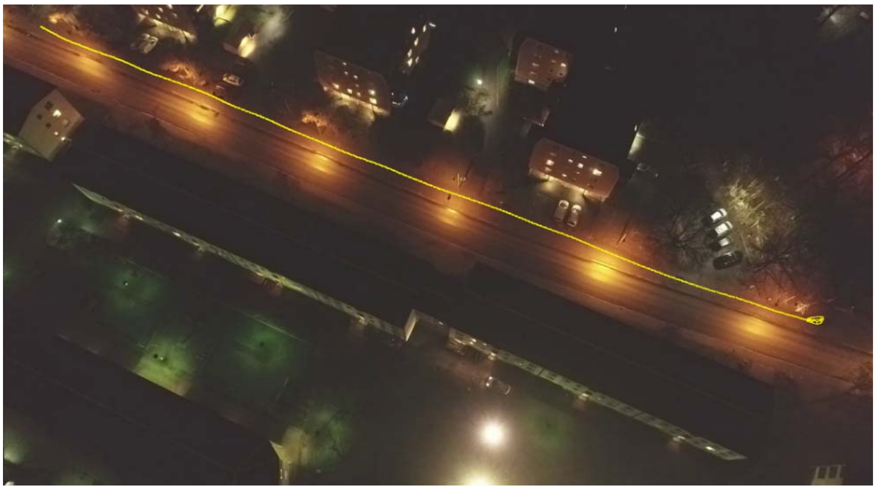

Figure 8. Aerial view of the study area with annotated trajectory (Yastremska-Kravchenko et al., 2024b)

The number of points for each trajectory is heavily influenced by the road user's speed. Therefore, all trajectories were standardized by cropping them at identical start and finish positions. Subsequently, they were normalized using equally distributed points (0.1-meter steps) along the middle of the path as a new reference framework. As a result, all trajectories shared the same number of points, with two points having the same ID number but belonging to different trajectories corresponding to the same longitudinal position along the path. The lateral position was recalculated relative to the middle line of the path, where positive values indicated the right-hand side of the path in the direction of travel, and negative values indicated the left-hand side. Furthermore, data collected under electric lighting were associated with trajectory points, which were assigned the luminance value from the nearest measured illumination data point.

The video-recorded data were analysed in two steps: first, analysis of baseline data served as methodological exploration (refer to Yastremska-Kravchenko et al. (2024b)), and second, a large-scale data analysis, which included data from all five data collection periods and built upon the method from the first step (Yastremska-Kravchenko et al. (2024a)).

Methodological exploration

The methodological exploration conducted for baseline video data analysis aimed to investigate three questions:

1. Are there discernible differences in behaviour (such as chosen lateral positioning and speed) between pedestrians and cyclists in the experimental study compared to those in naturalistic settings?
2. How do lighting conditions (daylight versus electric lighting) influence the behaviour of pedestrians and cyclists on a micro-scale?

3. What patterns emerge in how cyclists utilize paths and position themselves relative to each other (particularly in bi-directional interactions) under varying lighting conditions?

The analysis was based on the trajectories obtained from the baseline at both locations. In total 146 trajectories from the experimental study and 326 from naturalistic conditions. For further details about the analysis, please refer to Yastremska-Kravchenko et al. (2024b).

We analysed the differences between the trajectories of pedestrians and cyclists, also testing for differences between the experimental study and naturalistic conditions. Specifically, we focused on profiles of average speed and lateral position, extracted from the T-Analyst software using the x, y coordinates of the road users' trajectories along the path. The disparities between the trajectories of these two groups of path users were statistically evaluated.

To assess the impact of lighting conditions on the path users' behaviour in terms of speed and lateral position at the individual level, we conducted separate analyses of movements under daylight and electric lighting.

Pedestrians results

Figure 9 illustrates the average speed and lateral positions of all recorded pedestrians in Linköping, providing valuable insights into their movement patterns and positioning on the shared-use path. The disparities in speed profiles between the two groups of pedestrians under both daylight and electric lighting conditions were found to be within a range of 0.2 m/s. There was no significant difference in average speed profiles between the groups under either lighting condition. However, a significantly more pronounced difference in lateral positioning between the pedestrian groups was observed during daylight hours.

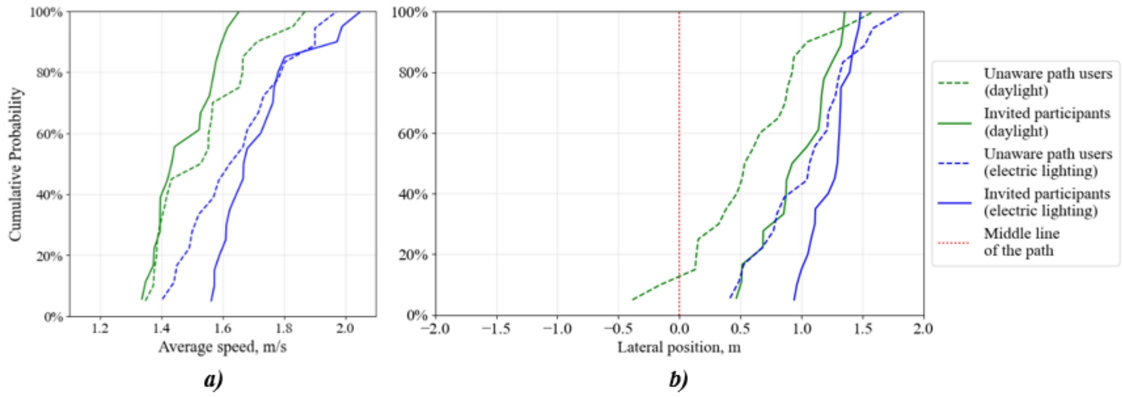

Figure 9. Average speed (a) and lateral position (b) in the different groups of pedestrians at the location in Linköping (Yastremska-Kravchenko et al., 2024b).

The visualisation in Figure 10 provides insights into the patterns of pedestrian behaviour in Lund. Similar patterns were noted on the path as in Linköping, with insignificant differences in speed profiles between the two groups of pedestrians under both daylight and electric lighting conditions. The disparity in lateral position between the two groups was also found to be insignificant under both lighting conditions.

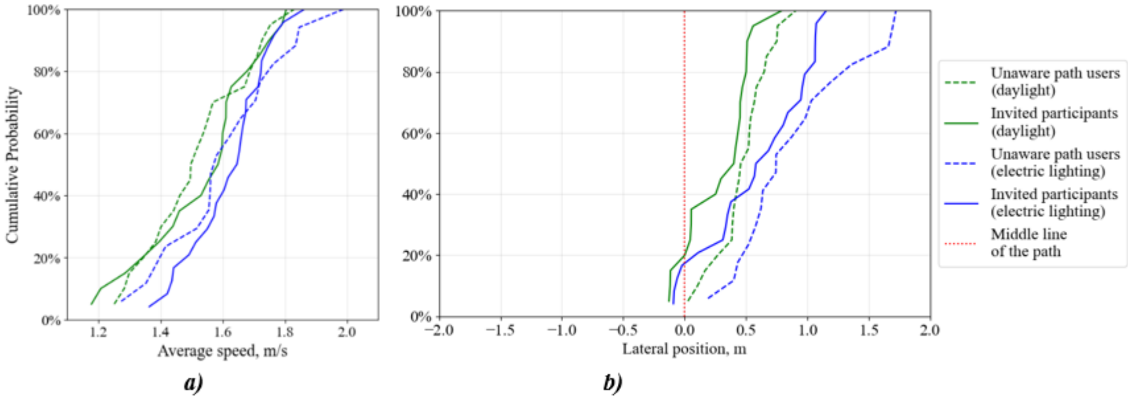

Figure 10. Average speed (a) and lateral position (b) in the different groups of pedestrians at the location in Lund (*Yastremska-Kravchenko et al., 2024b*)

Cyclists results

Figure 11 illustrates the average speed and lateral position profiles of two groups of cyclists on the shared-use path in Linköping under both daylight and electric lighting conditions.

During the examination of differences between the cyclists’ groups (for details please refer to Yastremska-Kravchenko et al. 2024b), it was observed that their average speed differed by more than 1 m/s, as depicted in Figure 11. This difference was found to persist across various lighting conditions.

Based on the observed trajectories, the lateral positions of the two groups of cyclists showed minimal variation under electric lighting conditions. However, only under daylight conditions difference in average lateral position from the middle of the path between the groups found to be statistically significant.

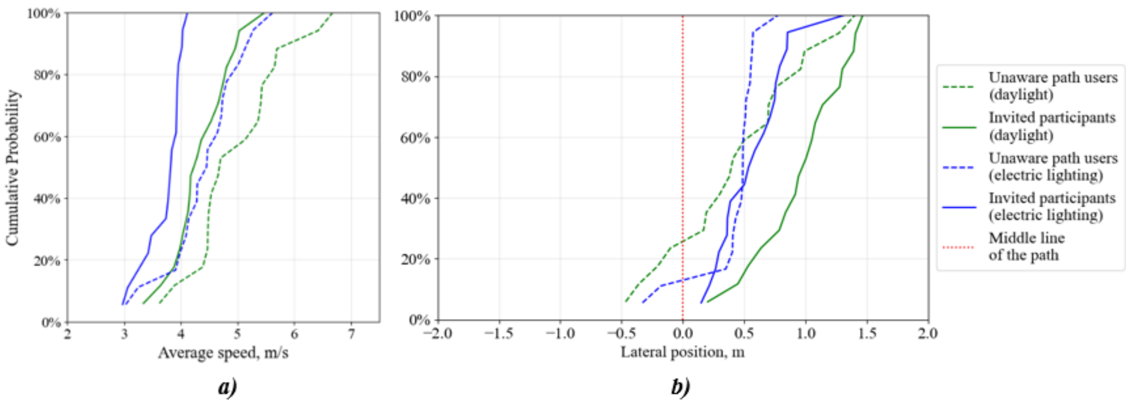

Figure 11. Average speed (a) and lateral position (b) of the different groups of cyclists at the study location in Linköping (Yastremska-Kravchenko et al., 2024b)

The identical analysis was conducted for the study location in Lund, as depicted in Figure 12. The observed microscopic behaviour revealed a distinction in speed profiles between the two groups of cyclists under both lighting conditions (refer to Figure 8a), but the positions of cyclists did not exhibit significant differences under the two lighting conditions (see Figure 12b).

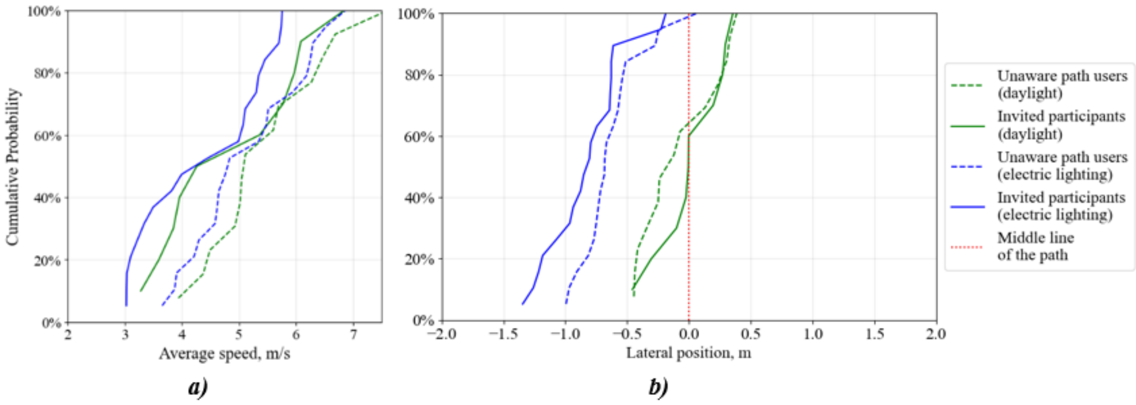

Figure 12. Average speed (a) and lateral position (b) for the different groups of bicyclists at the location in Lund (Yastremska-Kravchenko et al., 2024b).

Cyclists' behaviour in bi-directional interactions under varying lighting conditions (trajectory analysis)

Regarding the analysis aimed at addressing how bicyclists use paths and position themselves in relation to each other, our focus was shifted to one of the most common cyclists' interacting situations: bi-directional interactions, where they encounter each other while moving in opposite directions (Figure 13).

Figure 13. Studied interaction type (Yastremska-Kravchenko et al., 2024b)

We utilized only the naturalistic video-recorded data of bicyclists collected in Linköping. A total of 60 bi-directional interactions, comprising 120 trajectories, were selected, with an equal distribution between videos recorded during daylight hours and those captured under electric lighting conditions.

Similar to the study conducted by Yuan et al. (2018), a consistent interaction-related manoeuvre was observed in all bi-directional interactions. This manoeuvre involved cyclists initiating an evasive action during each head-on encounter, altering their intended trajectory by swerving to the right and thereby ensuring a greater passing distance. Building on this observation, we introduced a metric termed 'safe lateral passing distance' between cyclists (Figure 14), which refers to the lateral space maintained by cyclists before they meet and continue to maintain until they pass each other.

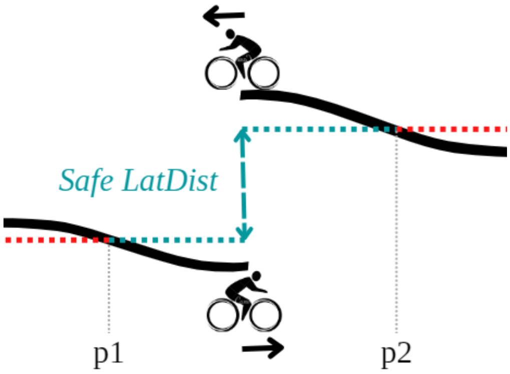

Figure 14. Illustration of the 'safe passing lateral distance' measure (Yastremska-Kravchenko et al., 2024b).

Based on the observations of the distribution of passing distances in various lighting conditions, which elucidate the dynamics of bi-directional interactions among cyclists, it is apparent that the difference in lateral space between daylight and electric lighting conditions was negligible, not exceeding 20 centimetres (for more details refer to Yastremska-Kravchenko et al. (2024b)). This suggests that bicyclists tend to maintain similar lateral distances during bi-directional interactions irrespective of lighting conditions. The findings further indicate that each pair of cyclists adjusted their positions to ensure a passing distance of at least 1.43 meters, measured from the centres of the two bicyclists. Consistent with previous considerations in this study, a safe lateral passing distance is defined as 1.5 meters, and it was observed to be maintained in 95% of the analysed bi-directional interactions.

The aggregation of longitudinal distances between two interacting cyclists at the moment when they established a safe lateral passing distance was plotted and compared. During daylight hours, cyclists adjusted their positions when they were further apart. At a longitudinal distance of 20 meters between the interacting cyclists, nearly 90% of pairs of cyclists in daylight had already achieved a safe lateral passing distance of 1.5 meters. In contrast, interactions recorded under electric lighting showed that only 75% reached a safe lateral passing distance at this longitudinal distance.

An alternative view of the findings focusing on time was obtained by Yastremska-Kravchenko et al. (2024b). This perspective incorporates the variable of speed, acknowledging that cyclists typically travel at varying speeds. The figure illustrates the amount of time remaining until the interacting cyclists pass each other when they reach a safe passing distance. This temporal analysis enhances our understanding of the dynamics of bi-directional interactions among cyclists by considering the interplay between time and speed. The results reveal a notable difference between the lighting conditions, indicating that 90% of cyclists in daylight reached safe lateral passing distances approximately 1.4 seconds earlier than those under electric lighting.

Assessments of speed and slalom used in the evaluation of interventions

The insights from these methodological explorations resulted in the choice of two specific microscopic behaviour to be used in the evaluation of interventions: speed and slalom. These analyses covered 353 individual trajectories of cyclists and pedestrians who experienced the path under various lighting conditions, including daylight and electric lighting (see Table 3). The trajectories were collected in the experimental study for further details about the analysis, please refer to the study by Yastremska-Kravchenko et al. (2024a).

The alterations in trajectories were assessed through speed and slalom profiles. Speed profiles were represented as the median value of each individual trajectory, chosen for its resilience against outliers, it is also robust against changes in the magnitude of values within the dataset, and it often provides more accurate measure of central tendency (Wilcox & Keselman, 2003; Washington et al., 2020).

Furthermore, the slalom measure (Figure 15) was employed to assess the extent to which a path user, whether a bicyclist or pedestrian, deviated from a straight line (baseline) while traveling along the path.

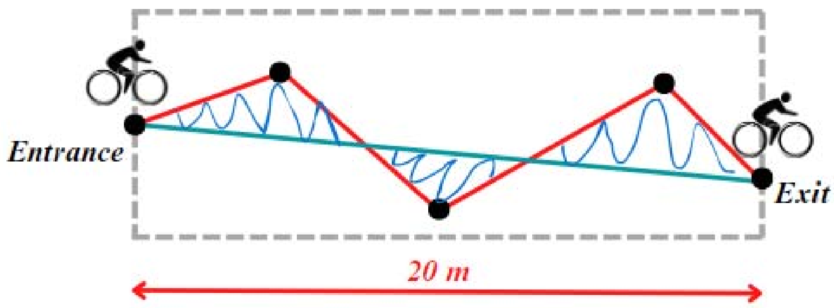

Figure 15. Illustration of the slalom measure (Yastremska-Kravchenko et al., 2024a).

Results

Overview of results

The results of the BELYSA-project show that pedestrian and cyclist perspectives on interventions along shared walk and cycle paths can, based on the theoretical conceptual framework, be systematically assessed. Different packages of environmental interventions change the results obtained by the technical measures, study participants experiences of the path and their microscopic behaviour. Tables 5 (Linköping) and 6 (Lund) summarise significant effects identified and the direction of the changes observed. The summaries reveal a consistent pattern in the significant effects identified. The environmental interventions are associated with changes in perceived stimuli represting assessments of upkeep, surface and lighting qualities, microscopic behaviour, and to a smaller extent conceptual environmental appraisals. Notably, pedestrian and cyclist experiences and behaviour somewhat differ.

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Table 5. Overview of significant effects of interventions on pedestrians' and cyclists' OBEA for daylight (DL) and electric light (EL) conditions in Linköping.

	Perceived stimuli													Environmental appraisal			Behaviour		Affective response		Theory of planned behaviour			Behavioural intention	
	PUDQs			Surface	Traffic	Social				POLQ		Prospect - refuge theory		Safety	Visual access	Restpotl	Speed	Slalom	Change Arousal	Change Valence	Attitude	Sub norm	PBC	Choose	Avoid
	Complex	Upkeep	Greenery			Conflict	Friendly	Crowding	Consideration	PSQ	PCQ	Prospect	Escape												
Linköping Baseline – Linköping Study 2																									
Pedestrians																									
DL		↑	↑																						
EL		↑	↑	↑	↑																				
Cyclists																									
DL																	↑				↑				
EL	↑	↑	↑	↑						↓															

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Table 5 continued. Overview of significant effects of interventions on pedestrians' and cyclists' OBEA for daylight (DL) and electric light (EL) conditions in Linköping.

	Perceived stimuli													Environmental appraisal			Behaviour		Affective response		Theory of planned behaviour			Behavioural intention	
	PUDQs			Surface	Traffic	Social				POLQ		Prospect - refuge theory		Safety	Visual access	Restpotl	Speed	Slalom	Change Arousal	Change Valence	Attitude	Sub norm	PBC	Choose	Avoid
	Complex	Upkeep	Greenery			Conflict	Friendly	Crowding	Consideration	PSQ	PCQ	Prospect	Escape												
Linköping Study 2 – Linköping Study 3																									
Pedestrians																									
DL		↓	↓													↓									
EL			↓							↑	↓						↓	↓						↑	
Cyclists																									
DL																			↑						
EL	↓		↓							↑				↑			↑	↓	↑						

Table 6. Overview of significant effects of interventions on pedestrians' and cyclists' OBEA for daylight (DL) and electric light (EL) conditions in Lund.

	Perceived stimuli													**Environmental appraisal**			**Behaviour**		**Affective response**		**Theory of planned behaviour**			**Behavioural intention**	
	PUDQs			Surface	Traffic	Social				POLQ		Prospect-refuge theory		Safety	Visual access	Restpotl	Speed	Slalom	ChangeArousal	Change Valence	Attitude	Sub norm	PBC	Choose	Avoid
	Complexity	Upkeep	Greenery			Conflict	Friendly	Crowding	Consideration	PSQ	PCQ	Prospect	Escape						Complexity	Upkeep	Greenery			Conflict	Friendly
Lu Baseline – Lund Study 2																									
Pedestrians																									
DL				↑																					
EL		↑		↑		↓	↓	↓		↑					↑		↓	↓							
Cyclists																									
DL				↑													↑	↓							
EL		↑		↑		↓				↑	↑						↑	↓			↑	↑			

Evaluation of interventions

Baseline: TEA lighting conditions

The measurements of horisontal illuminance (lx) at baseline showed how the light levels varied along the path in Linköping (16). The illuminance largely met the requirements of 10 lx (Swedish Transport Administration, 2020). Table 7 summarizes the results from the manual measurements on the path in Linköping during baseline. The mean illuminance, $\bar{E}$ [lx] has been calculated as the arithmetic mean of the point values. Minimum illuminance, E_{min} [lx] is the minimum horizontal illuminance at the cycle path, i.e. the lowest measured value at any point. Illumination uniformity is calculated as the ratio between the lowest point value and the mean value of all point values, i.e. $E_{min}/\bar{E}$.

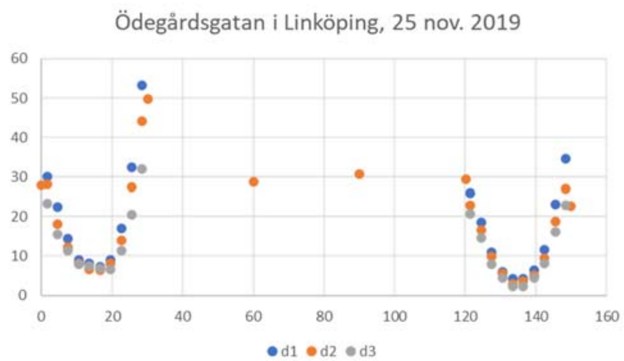

Figure 16. Horizontal illuminance (Lux) measured manually under each lamppost and on the brightest (between lamppost 1 and 2) and darkest (between lampposts 5 and 6) sections of the path in Linköping in November 2019.

Table 7. Manually measured horizontal Illuminans and Luminance during baseline in Linköping

Section	Baseline, 25 nov. 2019
Lightest section, $\bar{E}$ [lx]	17,33
Lightest section, E_{min} [lx]	6,40
Lightest section, $E_{min}/\bar{E}$	0,37
Darkest section, $\bar{E}$ [lx]	12,4
Darkest section, E_{min} [lx]	2,20
Darkest section, $E_{min}/\bar{E}$	0,18
The whole path, $\bar{E}$ [lx]	14,87
The whole path, E_{min} [lx]	2,20
The whole path, $E_{min}/\bar{E}$	0,15
Luminance [cd/m^2], darkest spot	0,6
Luminance [cd/m^2], lightest spot	2,14

The dynamic measurement of illuminance with the BMT more clearly shows the variation in illuminance along the path, with significantly higher values under the lampposts and darker areas in between (17). After the initial illuminance

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measurement with the BMT, the luxmeters placed on the side of the frame were not considered relevant, in this case following the same pattern as the luxmeter mounted on the top but with lower values (Figure 17), but in other cases generating invalid values (Figure). It was decided to only focus on the results from the top mounted luxmeter for the analyses further on.

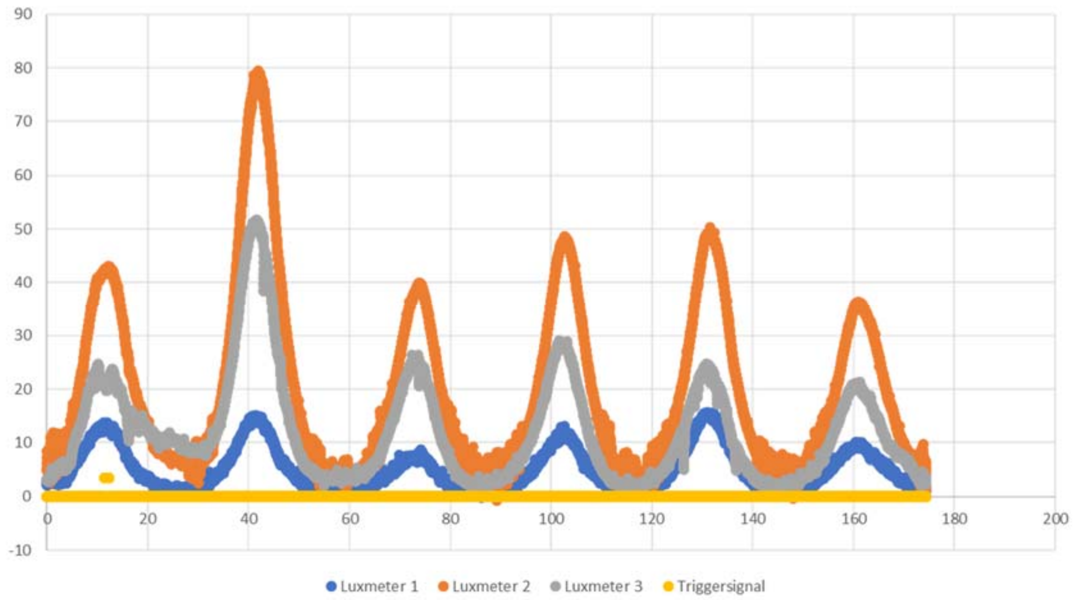


Figure 17. Illuminance measured dynamically with the BMT in the middle of the test section in Linköping on March 5th, 2020. Luxmeter 2 was mounted on top of the frame at a height of 1,09 meters from the ground, luxmeter 1 on the side of the frame furthest from the lampposts and luxmeter 3 on the side facing the lampposts.

The baseline measures of illuminance in Lund revealed very low levels, mostly below the 10 lx required for pedestrian paths (Swedish Transport Administration, 2020).

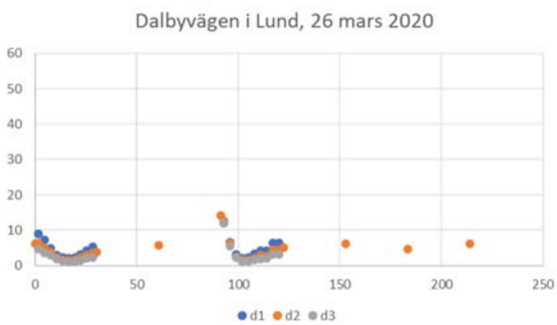


Figure 18. Horizontal illuminance (Lux) measured manually under each lamppost and on the brightest (between lamppost 4 and 5) and darkest (between lampposts 1 and 2) sections of the path in Lund in march 2020.

Table 8 summarises the results from the manual measurements on the path in Lund during baseline. The variation in illuminance along the path, with higher values closer to the light sources and darker areas in between is illustrated from the dynamic measurement of illuminance with the BMT (Figure).

Table 8. Manually measured horizontal Illuminans and Luminance during baseline in Lund.

Section	Baseline, 26 mars 2020
Lightest section, $\bar{E}$ [lx]	4,22
Lightest section, E_{min} [lx]	1,20
Lightest section, $E_{min}/\bar{E}$	0,28
Darkest section, $\bar{E}$ [lx]	3,27
Darkest section, E_{min} [lx]	1,10
Darkest section,, $E_{min}/\bar{E}$	0,34
The whole path, $\bar{E}$ [lx]	3,74
The whole path, E_{min} [lx]	1,1
The whole path, $E_{min}/\bar{E}$	0,29
Luminance [cd/m^2], darkest spot	0,1
Luminance [cd/m^2], lightest spot	1*

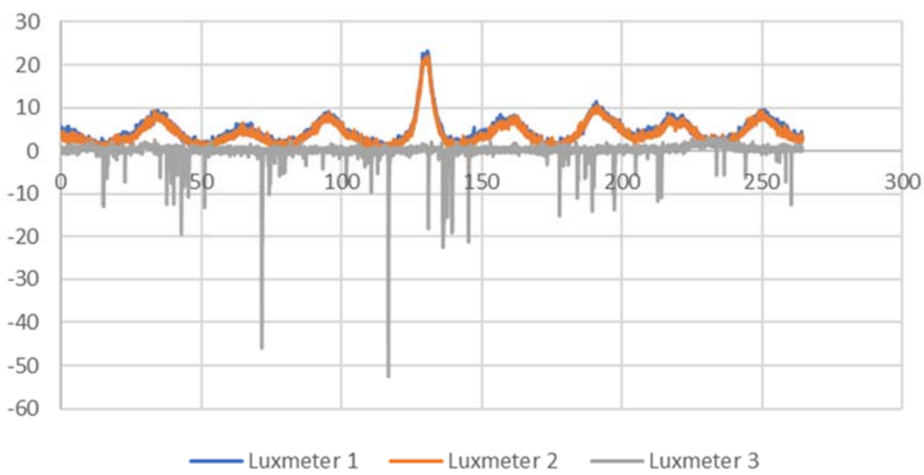


Figure 19. Illuminance measured dynamically with the BMT in the middle of the test section in Lund on March 26th, 2020. Luxmeter 2 was mounted on top of the frame at a height of 1,09 meters from the ground, luxmeter 1 on the side facing the light sources and luxmeter 3 on the side furthest from the ligth sources.

TEA road surface condition

RMS values (Root Mean Square) for the transverse profiles measured with the laser has been calculated to illustrate to illustrate possible differences of the road surfaces before and after interventions. Other metrics have not been considered sufficiently reliable and even for the reported RMS values there are inaccuracies. **Figure** shows the RMS values for the path in Linköping, before and after intervention – the higher the value, the rougher the surface. During the measurements after the intervention, the surface was wet with many leaves from the trees beside the path, which affected the measurement. The measured values include the unevenness caused by the leaves which do not represent unevenness in the asphalt surface itself. Although the surface was brushed before the measurement, there were still many leaves left on the surface. In Figure , the measured surfaces are depicted using the intensity images from the laser - the surface was dry and clean during baseline (picture on the left), while wet and covered with leaves when measuring after the intervention (picture on the right). The images also show that the surface is darker after the intervention with new asphalt surface. The object shown in the middle of the left picture is a manhole cover, which in the picture looks a bit distorted (this also applies to the road marking in the right picture). This is a result of the movements of the BMT, which that needs to be accounted for when measuring and analysing the longitudinal profile. That is why we need an accelerometer mounted on the BMT (Larsson et al., 2023), which was not in place in the beginning of this project.

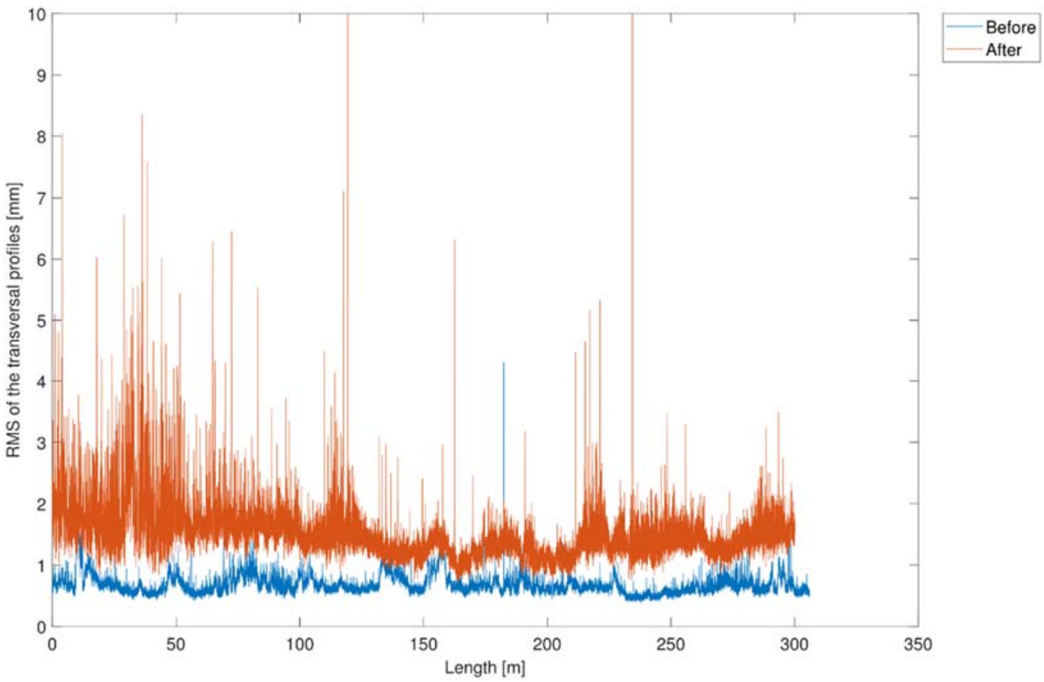


Figure 20. RMS values of the transversal profiles measured with the linelaser on the path in Linköping before and after intervention.

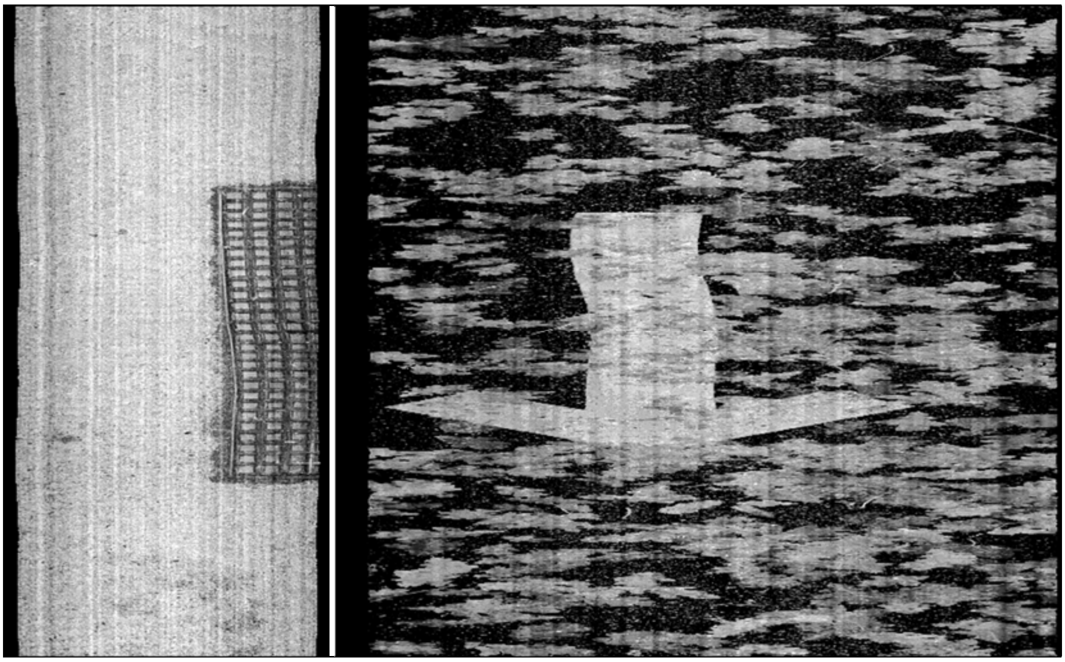


Figure 21. Images showing the intensity of the lasersignal illustrating the path surface before (to the left) and after (to the right) the intervention in Linköping.

Figure 22 shows the RMS values for the path in Lund, before and after intervention. The results suggest that the newly laid pavement in Lund was smoother than the old surface, while this is not the case in Linköping. However, due to the large amount of leaves on the surface during the after-measurement in Linköping these results can be questioned. In Figure 23, the laser intensity images from Lund are showing that the surface during baseline measurements was clean and dry (picture on the left), while there were leaves on the surface during the after-measurement (picture on the right). The surface is also slightly darker due to the new asphalt.

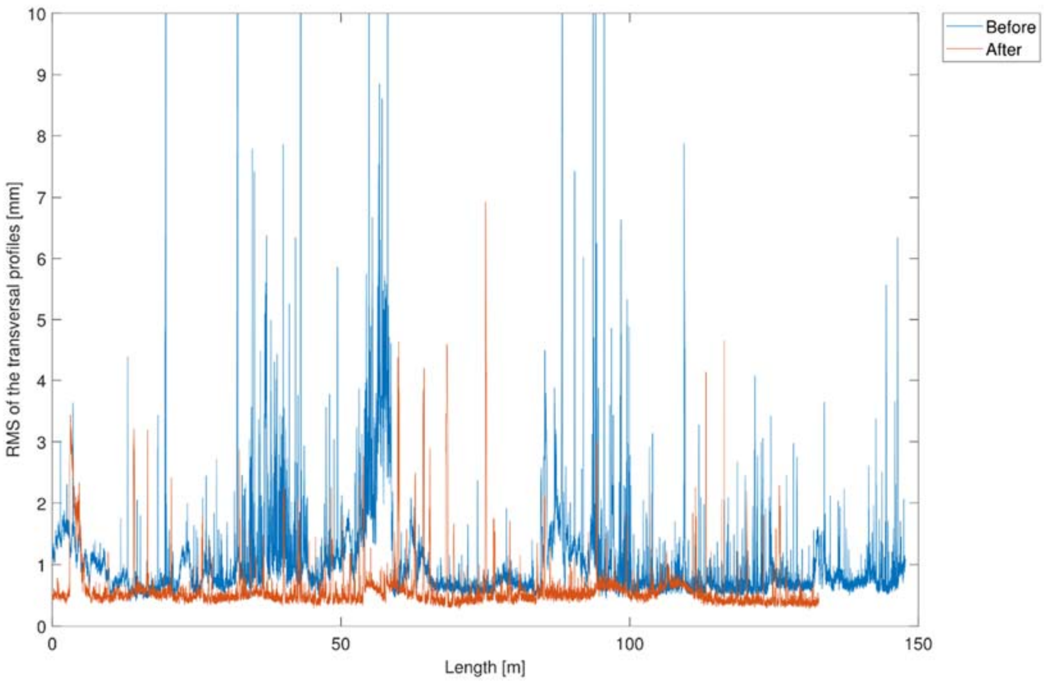


Figure 22. RMS values of the transversal profiles measured with the linelaser on the path in Lund before and after intervention.

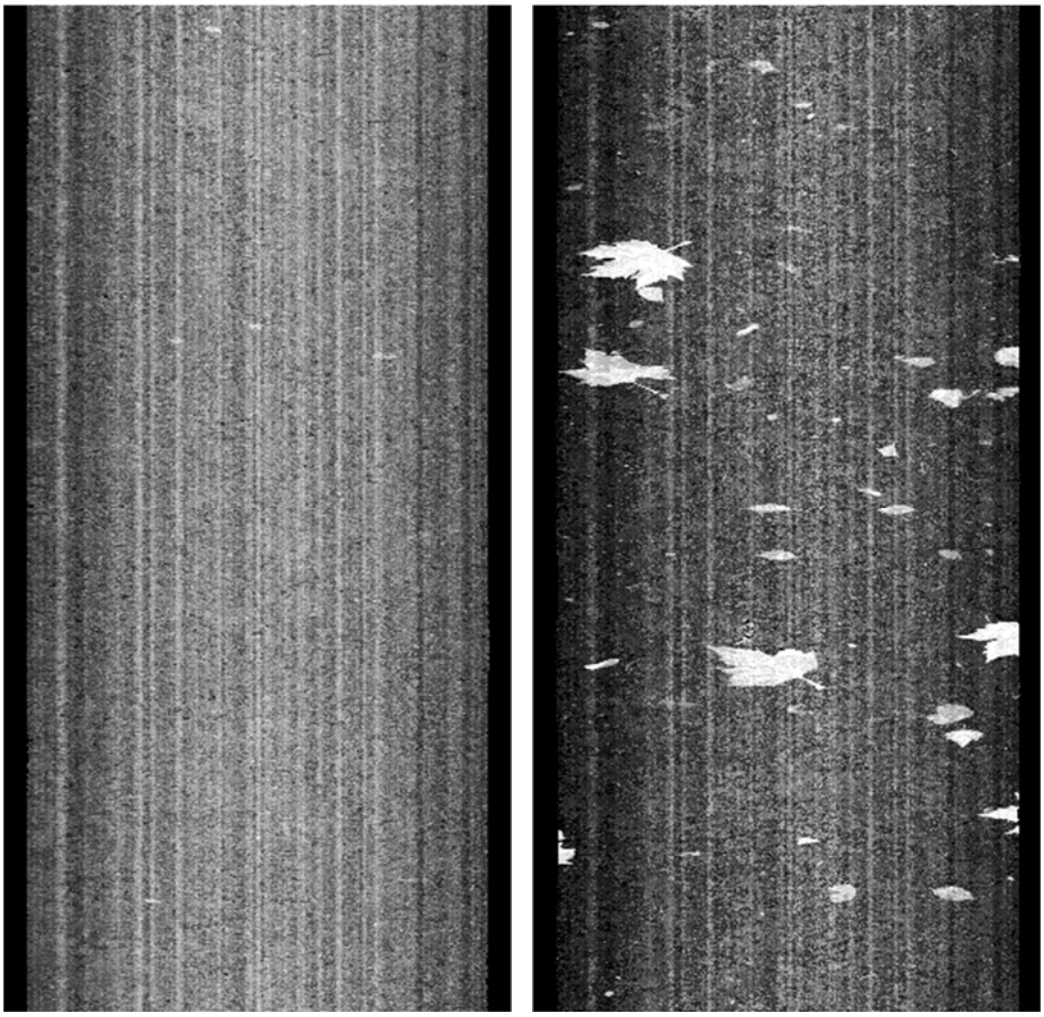


Figure 23. Images showing the intensity of the lasersignal illustrating the path surface before (to the left) and after (to the right) the intervention in Lund.

Electric lighting and microscopic behaviour

Further exploration into the potential influence of electric lighting on microscale speed changes involved conducting correlation analysis between measured manually horizontal illuminance levels and speed profiles. In both studied locations, the relationship between illuminance and speed was tested using 20 trajectories of cyclists and an equal number of unaware pedestrians moving undisturbed along the path under electric lighting.

Figure 24 depicts the outcomes of a correlation analysis between the manually measured horizontal illuminance levels and speed profiles within the naturalistic sample at the two study locations: Linköping (a) and Lund (b). Each data point (blue dot) represents an individual trajectory point, with the illuminance (lx) values aligned with the position along the path and the speed values normalized to the average speed for each distinct trajectory.

There was found only a negligible correlation observed between illuminance (lx) and average speed (m/s). Nonetheless, for bicyclists at both locations, the positive correlation was considered statistically significant (for more details refer to Yastremska-Kravchenko et al. (2024b).

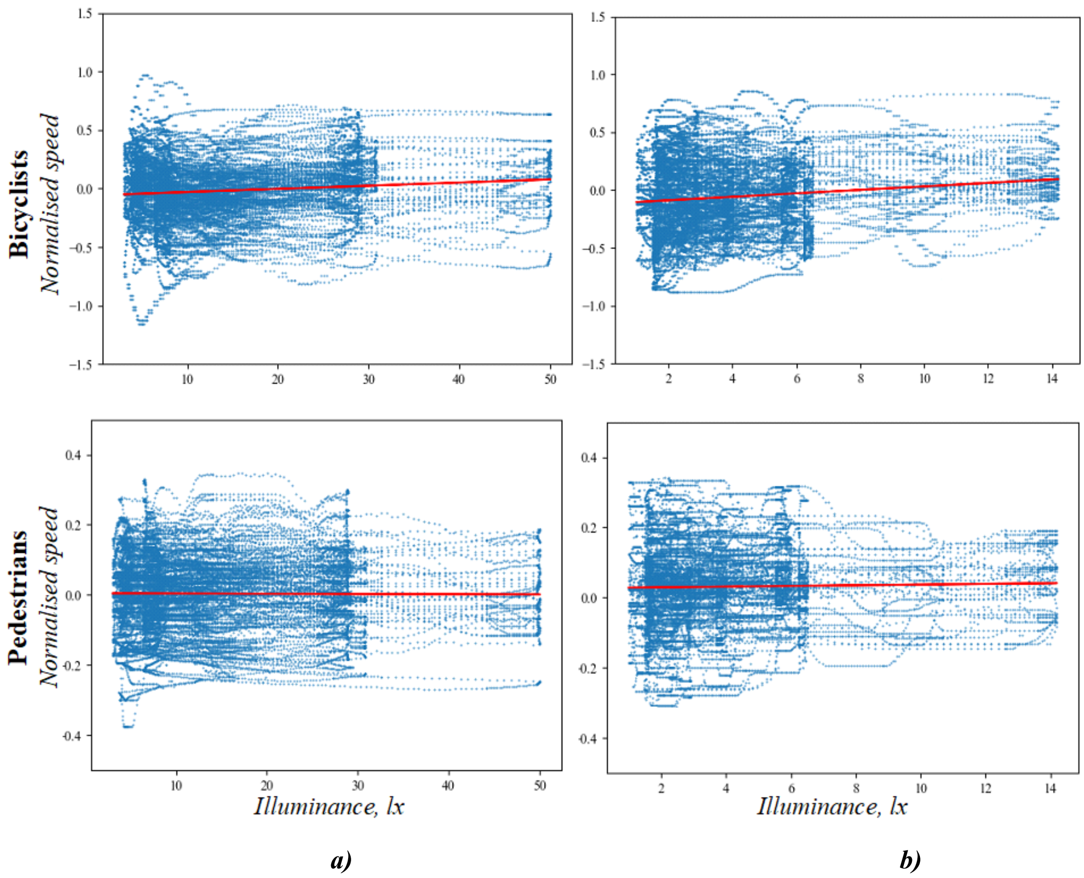


Figure 24. Correlation between illuminance and speed: a) Linköping, b) Lund. The red line represents a LOESS curve (Yastremska-Kravchenko et al., 2024b)

Energimyndigheten

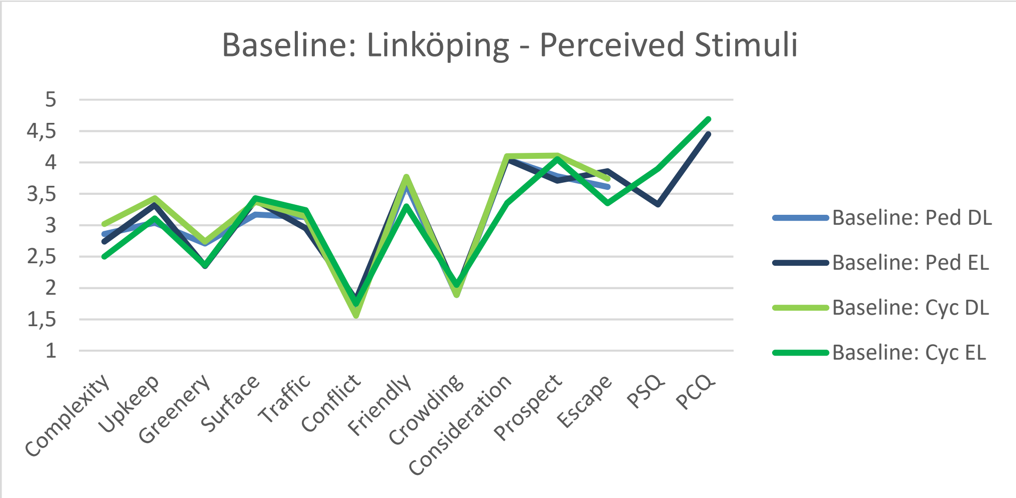
Baseline: observer-based environmental assessments

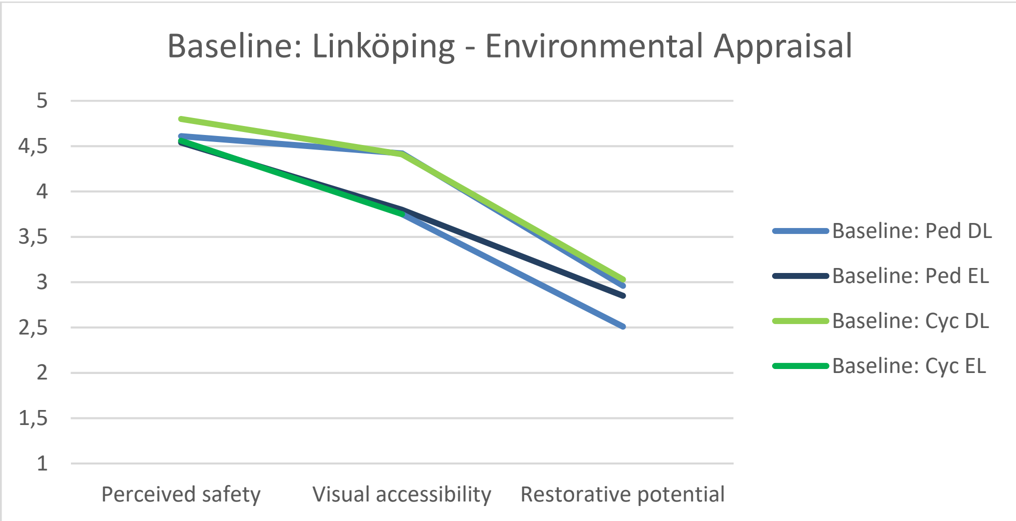
The baseline assessment of the perceived stimuli in Linköping shows average assessments with regard to the perceived stimuli of complexity and asthetics, upkeep, presence of greenery, surface quality and intensity of traffic. Assessments of social aspects show that the presence of conflicts between road users are perceived as low and this result is in accordance with a low assessment of crowding. The social atmosphere is regarded as friendly and people are reported to show consideration.

Overarchingly the path is assessed to have a good prospect and offer possibilities for escape. The assessments in electric lighting conditions show that the perceived strength of the light is as assessed as intermediate, with mean values slightly below the mid-point of the scale (pedestrians m = 3.33 and cyclists m = 3.90, index from 1 = low strength to 7 = high strength). The perceived quality of the light seems however satisfactory with mean values slightly towards the higher end of the scale (pedestrians m = 4.45 and cyclists m = 4.69, index from 1 = low quality to 7 = high quality).

As for the environmental appraisals, the perceived safety is assessed as high during both daylight and electric lighting conditions. The perceived visual accessibility is on average assessed as above the mid-point of the scale, indicating that it is possible to see and orientate also during electric light. However, the restorative potential is assessed as relatively low. The differences in affective responses of valence and arousal were negligible.

The participants attitude towards walking and cycling along the path is somewhat positive, as well as the perceived subjective norm and behavioural control to do so. These results are in line with the intention to choose the path, and the low intention to avoid walking/cycling along the path. All mean values are depicted in Figure 25. For further details please refer to Rahm et al., 2024b.





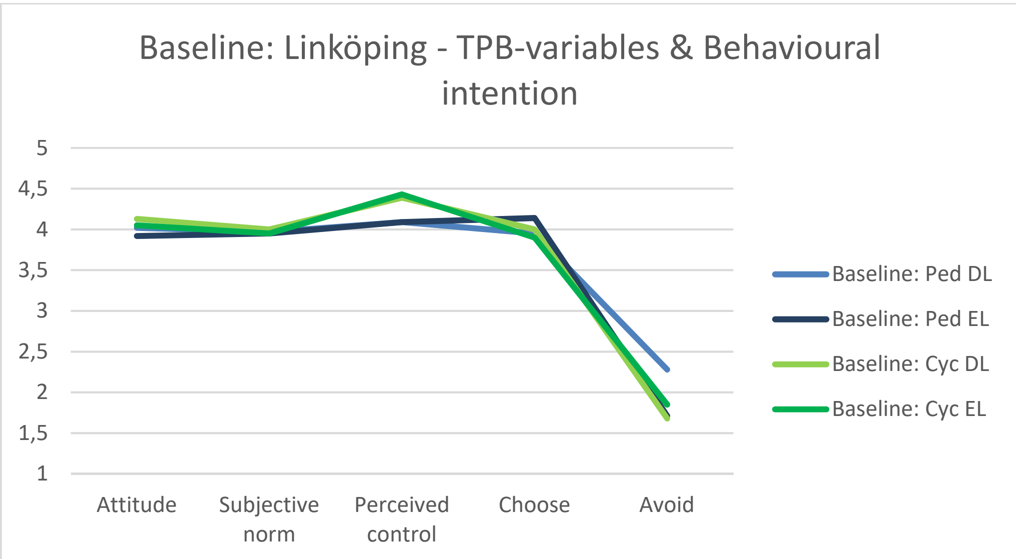
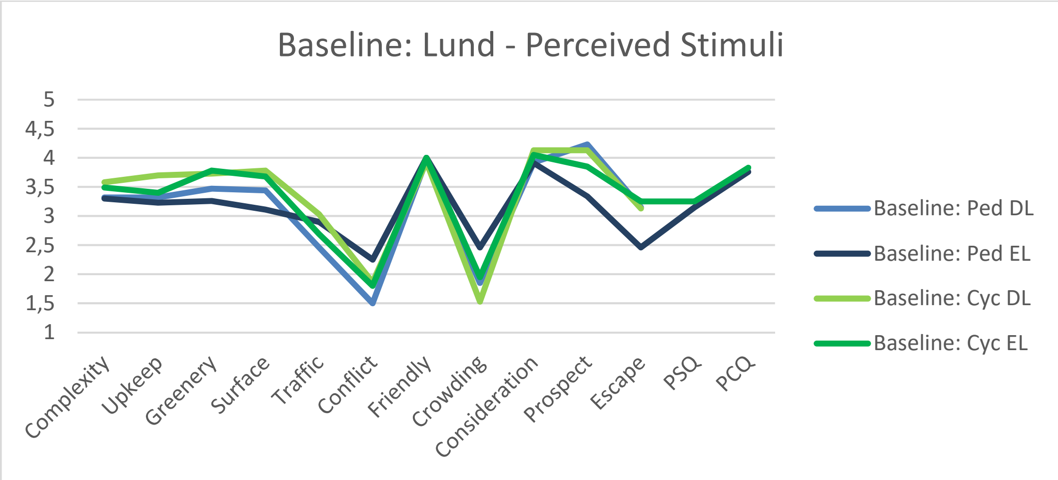


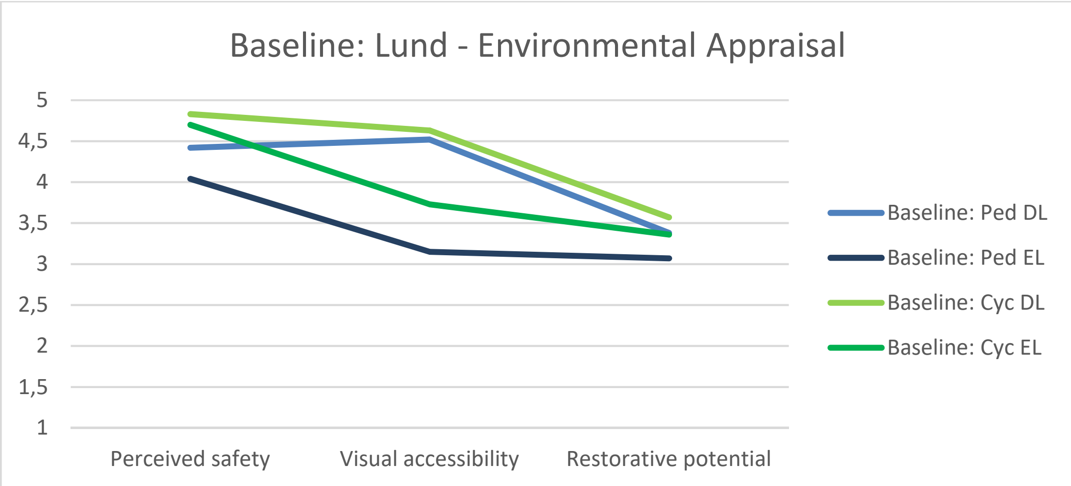
Figure 25. Mean values for participants (pedestrians and cyclists) baseline assessments of perceived stimuli, environmental appraisals, variables from Theory of Planned Behaviour (TPB) and self-reported intention to choose and avoid the path. DL – daylight, EL – electric light

Also in Lund the perceived stimuli centre around the mid-point of the scale with average assessments of complexity and aesthetics, upkeep, greenery, surface and traffic. Conflict and crowding is assessed as low, and friendliness and consideration towards the higher end of the scale. Prospect is considered good during daylight, but average in electric light conditions. Escape is in daylight towards the mid-poing of thes scale but somewhat low in electric lighting. The perceived lighting quality of strength is intermediate and the comfort quality is assessed as quite high.

The assessments of environmental appraisals show that the path is perceived as rather safe, the visual accessibility is high in daylight but less so in electric lighting. The path seem to hold some restorative potential, especially in daylight. The differences in affective responses were also in Lund negligible.

Also in Lund the participants' attitude towards walking and cycling along the path is positive, as well as the perceived subjective norm and the perceived behavioural control. These results are in line with the high intention to choose the path, and the low intention to avoid it. All mean values are depicted in Figure 26. For further details please refer to Rahm et al., 2024b.





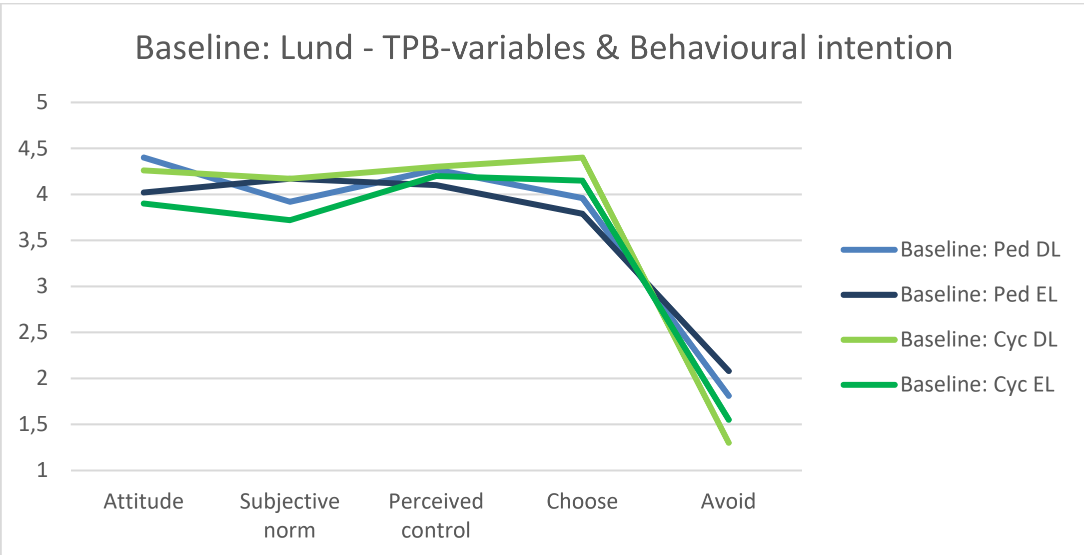


Figure 26. Mean values for participants (pedestrians and cyclists) baseline assessments of perceived stimuli, environmental appraisals, variables from Theory of Planned Behaviour (TPB) and self-reported intention to choose and avoid the path. DL – daylight, EL – electric light

Differences in OBEAs at baseline between location, transport mode and light conditions

The baseline assessments of the OBEAs tested for any differences in the response variables due to location (Linköping/Lund), transport mode (walk/cycle), and lighting condition (daylight/electric light). The analyses revealed effects on all levels of the reponse-variables associated with the physical environment (i.e. perceived stimuli, conceptual environmental appraisals and affective responses) whereas no effects could be identified for the variables derived from Theory of Planned Behavior (i.e. attitude, subjective norm and perceived behavioural control). The behavioural intention of avoiding the path differed between pedestrians and cyclists. Table 9 provides an overview of significant results.

Unsurprisingly the two locations significantly differ in several of the perceived stimuli. Also there are significant differences in conceptual environmental appraisals with visual accessibility assessed as higher in DL and EL, more over greenery seems more pertinent in DL than EL. Generally, pedestrians assess surface quality and safety as lower than cyclists. In addition several interaction effects were identified with location. More details for the analyses are provided in Table 9 (see also Rahm et al., 2024a)

Table 9. Results from the statistical analyses. Significant differences are marked with bold. Results not supported by the robust 3-factor ANOVAs are marked with *. Adapted from Rahm et al., 2024a)

Response variable	Linköping / Lund	Walk / Cycle	DL / EL	Interaction	Comments
Perceived stimuli					
Complexity & aesthetics	p<.001	n.s.	n.s.	n.s.	Lund>Linköping
Upkeep & order	n.s.	n.s.	n.s.	n.s.	
Well-maintained greenery	p<.001	n.s.	n.s.	n.s.	Lund>Linköping
Perceived surface quality	n.s.	p<.05	n.s.	n.s.	Cycle>Walk
Perceived traffic environment	p<.01	n.s.	n.s.	p<.05 Location* Walk/Cycle* DL/EL	Lund>Linköping Linköping: Day>Night Lund: DL<EL Walk: DL<EL Cycle: DL>EL
Perceived social atmosphere	n.s.	n.s.	n.s.	n.s.	
Perceived strength quality	n.s.	n.s.	n/a	n.s.	
Perceived comfort quality	p<.001	n.s.	n/a	n.s.	Linköping>Lund
Prospect	n.s.	n.s.	n.s.	n.s.	
Escape	p<.001	n.s.	n.s.	p<.05 Location* Walk/Cycle	Linköping>Lund Linköping: Walk>Cycle Lund: Walk<Cycle

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Table 9 continued.

Environmental appraisal					
Perceived visual accessibility	n.s.	n.s.	p<.001	p<.05 Location* DL/EL	DL>EL DL: Linköping<Lund EL: Linköping>Lund
Perceived safety	n.s.	p<.01	n.s.*	p<.05 Location* Walk/Cycle	Walk<Cycle Walk: Linköping>Lund Cycle: Linköping<Lund
Perceived restorative potential	p<.001			p<.05	Lund>Linköping DL>EL
Affective response					
Difference in arousal	n.s.	p<.01	n.s.	n.s.	Walk<Cycle
Difference in valence	n.s.	p<.05	n.s.*	n.s.	Walk<Cycle
Theory of planned behaviour					
Attitude towards the behaviour	n.s.	n.s.	n.s.	n.s.	
Subjective norm	n.s.	n.s.	n.s.	n.s.	
Perceived behavioural control	n.s.	n.s.	n.s.	n.s.	
Behavioural intention					
Choose a similar path	n.s.	n.s.	n.s.	n.s.	
Avoid a similar path	n.s.	p<.05	n.s.	n.s.	Walk>Cycle

Technical environmental assessments of lighting interventions

In Linköping the illuminance decreased when the new light source introduced in the second intervention. However the light distribution became more even over the test section (Table 10 and Figure 27). The dynamic measurement of illuminance with the BMT gives a nice illustration of the variation in "brightness" along the cycle path, but since the luxmeter is mounted about one meter above the ground it doesn't provide the correct values in relation to the standard. To compare the difference in lighting conditions before and after interventions, we have therefore used the manual measurements performed according to standard with values from a number of points between two lampposts, where the number of points and their location depends on the width of the path and the distance between the lampposts. Since the lighting conditions varies along the path we decided to measure on the lightest and darkest sections respectively, to get a more truthful picture

During both baseline in November 2019 and after the first intervention in October 2021 the same luminaires were used. The differences in illuminance between these two occasions are probably due to differences in foliage of the trees. After the second intervention in November 2022, the luminaires had been replaced with LED-lighting, resulting in lower average illuminance ($\bar{E}$) but with increased E_{min} and uniformity. We tried to do the measurements during the same time of year to have as similar conditions as possible, but the foliage of the trees were difficult to account for and hence the measurements are not completely comparable.

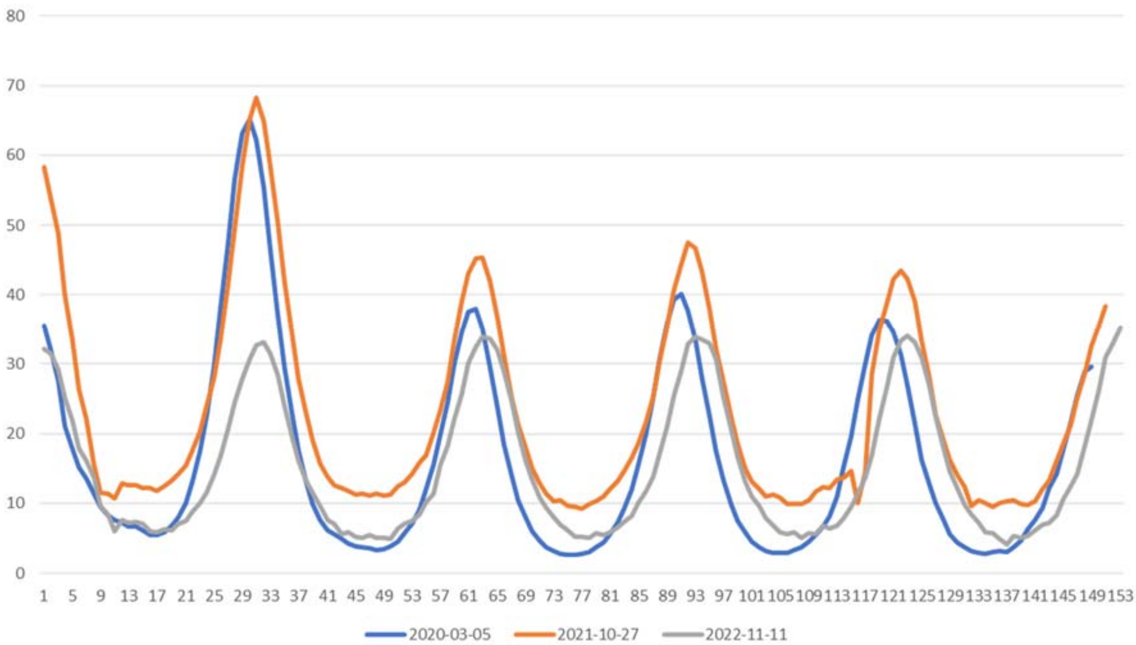


Figure 27. Illuminance measured dynamically with the BMT in the middle of the test section in Linköping with the top mounted Luxmeter at a height of 1,09 meters from the ground, at three different occasions: before the reconstruction of the path (March 5th, 2020), after reconstruction of the path but before the change in lighting source (October 27th, 2021) and after the change in lighting source (November 11th, 2022). The difference in longitudinal position is related to the need to calibrate the length measurement of the BMT before each measurement.

Table 10. Manually measured horizontal Illuminans and Luminance in Linköping

Section	*Baseline, 25 nov. 2019*	**Intervention 1, 13 okt. 2021**	**Intervention 2, 10 nov. 2022**
Lightest section, $\bar{E}$ [lx]	*17,33*	13,23	12,70
Lightest section, E_{min} [lx]	*6,40*	1,30	5,70
Lightest section, $E_{min}/\bar{E}$	*0,37*	0,10	0,45
Darkest section, $\bar{E}$ [lx]	*12,4*	10,50	11,71
Darkest section, E_{min} [lx]	*2,20*	0,50	3,00
Darkest section, $E_{min}/\bar{E}$	*0,18*	0,05	0,26
The whole path, $\bar{E}$ [lx]	*14,87*	11,87	12,21
The whole path, E_{min} [lx]	*2,20*	0,50	3,00
The whole path, $E_{min}/\bar{E}$	*0,15*	0,04	0,25
Luminance [cd/m^2], darkest spot	*0,6*	0,15	0,75
Luminance [cd/m^2], lightest spot	*2,14*	1,70	1,75

In Lund the illuminance significantly increased after the first intervention, which also included a changes in the electric lighing. After the intervention the illuminance level was also more evenly distributed over the path than before the change. Figure 28 illustrates the illuminance measured dynamically with BMT and 11 summarizes the results from the manual measurements on the path in Lund for each measurement occasion. After the intervention the lighting conditions was clearly improved with increased average illuminance ($\bar{E}$), E_{min} and uniformity

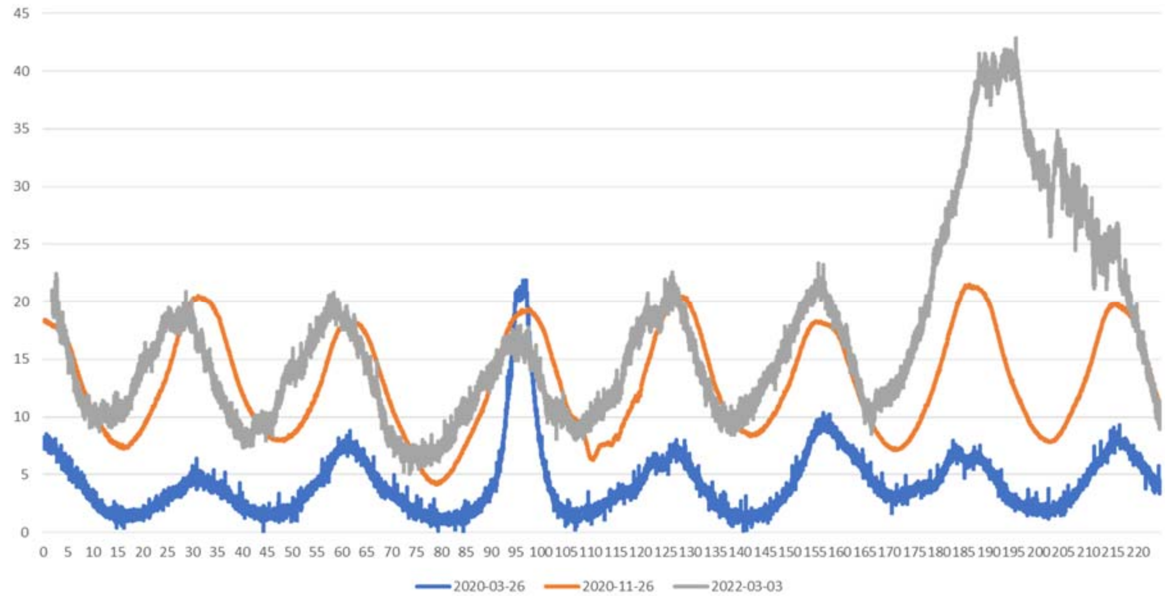


Figure28. Illuminance measured dynamically with the BMT in the middle of the test section in Lund with the top mounted Luxmeter at a height of 1,09 meters from the ground, at three different occasions: before the change in lighting sources (March 26th, 2020), after the change in lighting source during fall (November 26th, 2020) and during spring (March 3rd, 2022). Lighting at a construction site close by the cycle path interfered with the measurement performed in March 2022 explaining the peak values measured at the end of the section.

Table 11. Manually measured horizontal Illuminans and Luminance in Lund.

Section	*Baseline, 26 mars 2020*	Intervention, 3 mars 2022
Lightest section, $\bar{E}$ [lx]	*4,22*	11,37
Lightest section, E_{min} [lx]	*1,20*	7,75
Lightest section, $E_{min}/\bar{E}$	*0,28*	0,68
Darkest section, $\bar{E}$ [lx]	*3,27*	9,64
Darkest section, E_{min} [lx]	*1,10*	5,70
Darkest section,, $E_{min}/\bar{E}$	*0,34*	0,59
The whole path, $\bar{E}$ [lx]	*3,74*	10,50
The whole path, E_{min} [lx]	*1,1*	5,7
The whole path, $E_{min}/\bar{E}$	*0,29*	0,54
Luminance [cd/m^2], darkest spot	*0,1*	0,18
Luminance [cd/m^2], lightest spot	*1**	0,57

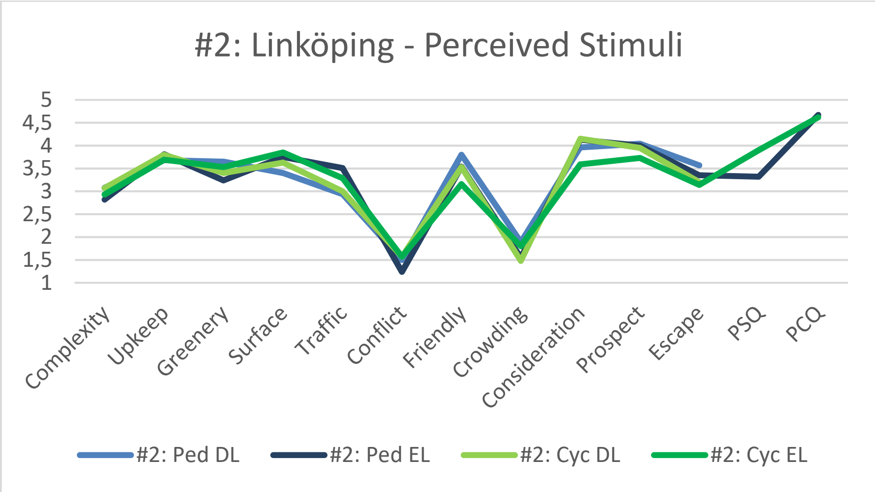
Energimyndigheten

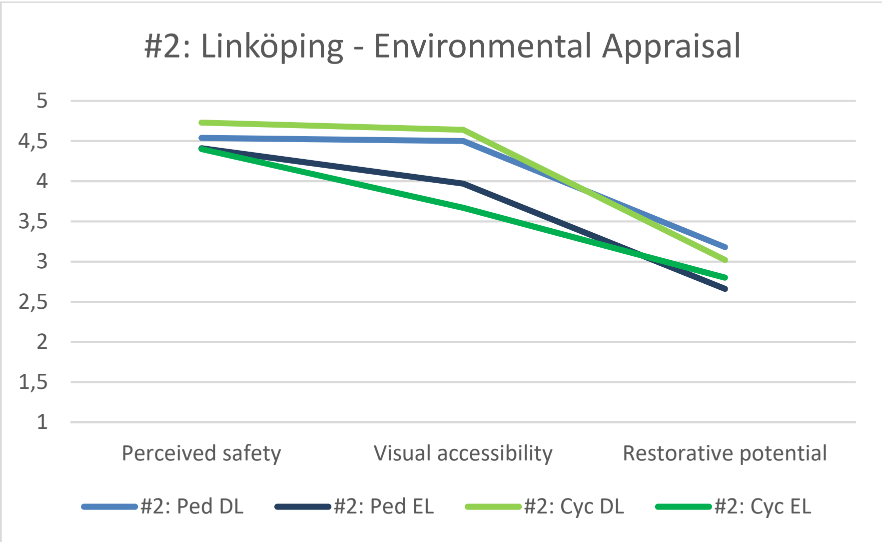
Observer-based environmental assessments after interventions

Effects of interventions on pedestrians and cyclists in Linköping

Figures 29 and 30 give overviews of the participants' assessments of the path in Linköping at the post-tests (Study 2 and Study 3). In response to the first intervention in Linköping assesments of upkeep quality of surface and maintenance of greenery consistently and signficantly increased from baseline to Study 2. Among pedestrians the effects on upkeep and greenery could be seen both in daylight and electric light (all p-values <.05), and surface in electric lighting (p <.05). As for cyclists, the corresponding effects were observed in electric lighting (all p < .05). Also the assessment of complexity increased (p <.05) and perceived strength quality of the light signficantly decreased. Similar to the pedestrians the effect on greenery was also observed in daylight (p<.05). No significant effects could be identified in the conceptual environmental appraisals. The favourable attitude towards cycling was significantly strentghtened (p<.05).

In Study 3, the assessments of upkeep decreased among pedestrians in daylight (p<.05) and the assessments of complexity among cyclists in electric lighting (p <.05). Whereas the assesments of greenery signficantly and consistently decreased among both pedestrians and cyclists and both lighting conditions (all p <.01). The assessment of perceived strength quality increased (all p <.05), and so did the change in affective response of arousal. However, the new electric lighting was assessed as lower in perceived comfort quality than the original lighting in the baseline assessment and Study 2 (all p <.001). Moreover, in the concepual environmental appraisals there was a decrease in perceived restorative potential among pedestrians during daytime (p <.05). No other signifcant differences could be identified in the OBEAs. For an overview of significant results please refer to Table 5.





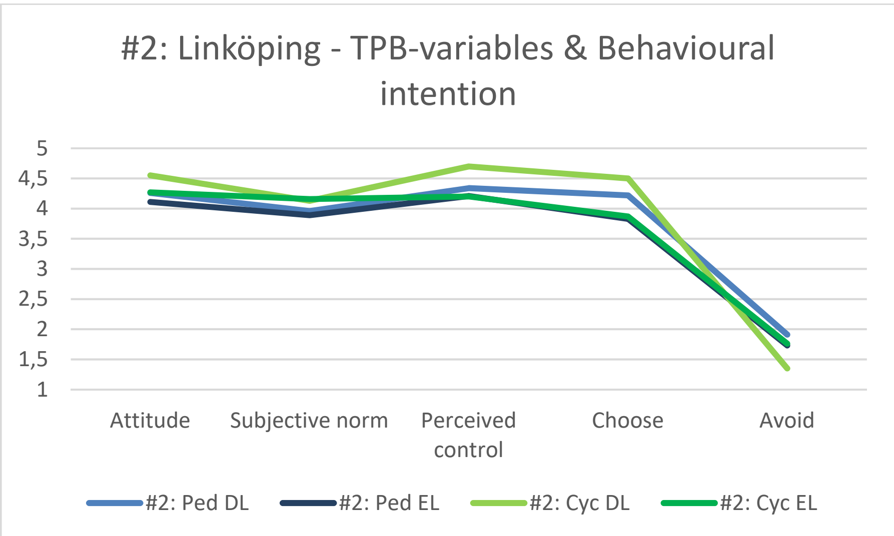


Figure 29. Linköping Study 2: Mean values for participants' (pedestrians and cyclists) assessments of perceived stimuli, environmental appraisals, variables from Theory of Planned Behaviour (TPB) and self-reported intention to choose and avoid the path. DL – daylight, EL – electric light

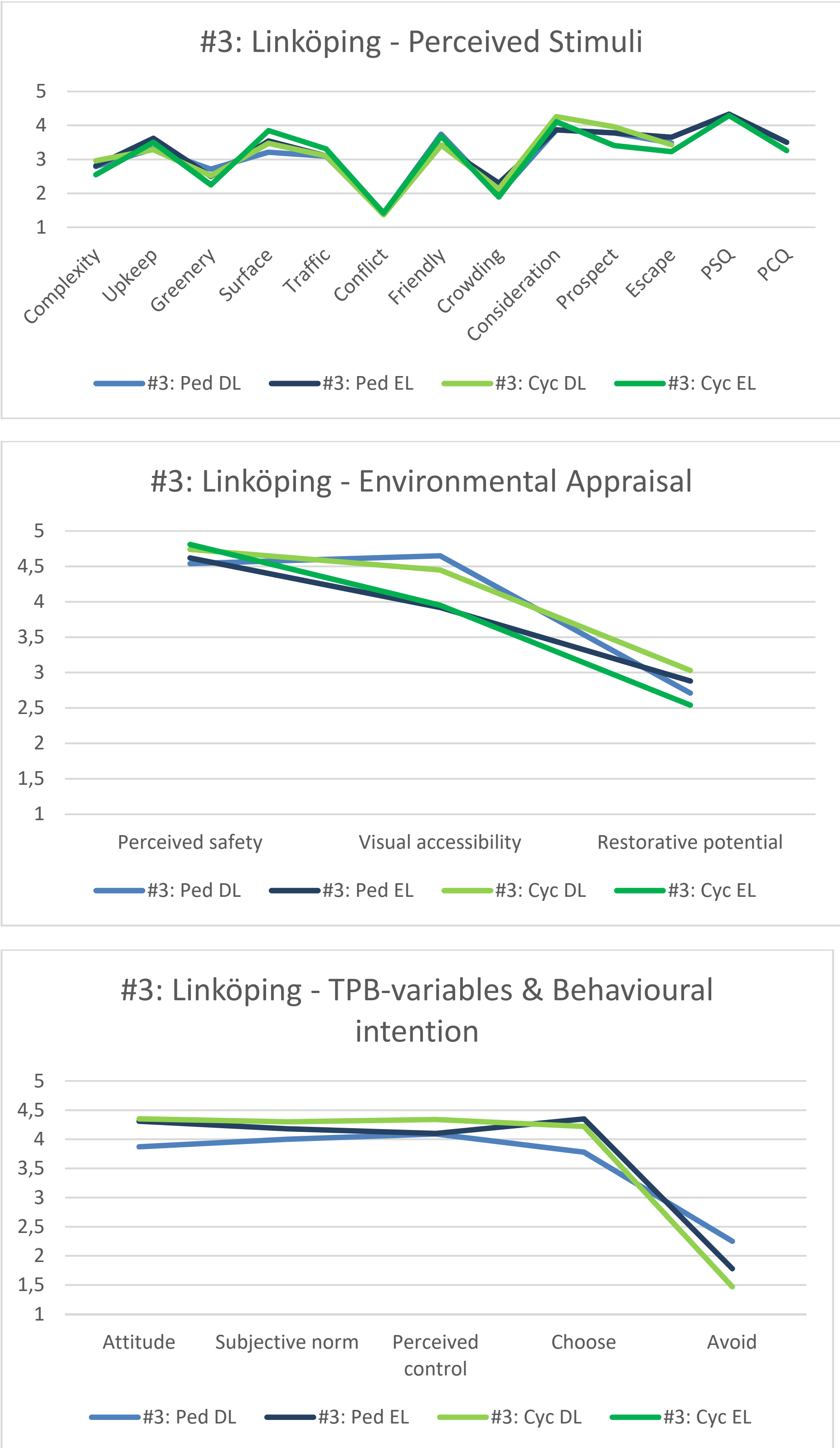


Figure 30. Linköping Study 3: Mean values for participants' (pedestrians and cyclists) assessments of perceived stimuli, environmental appraisals, variables from Theory of Planned Behaviour (TPB) and self-reported intention to choose and avoid the path. DL – daylight, EL – electric light

Effects of interventions on pedestrians and cyclists in Lund

Figure 31 gives an overview of the participants' assessments of perceived stimuli path in Lund at the post-test (Study 2). Generally, significant increases were identified surface in daylight and electric lighting conditions (all p-values < .05) and significant increases in upkeep in electric lighting (all p-values <.01). Moreover, in electric lighting signficant increases in the perceived lighting quality could be identified. The perceived strength quality significantly increased among both pedestrians and cyclists (all p-values <.01), whereas the perceived comfort quality increased among cyclists only (p <.05). In electric lighting also assessments of conflict decreased among both pedestrians and cyclists (all p-values <.05), asessements of crowding and friendliness decreased among pedestrians (all p-values <.05). As for the conceptual environmental appraisals the perceived visual accessiblity and safety increased among pedestrians (all p-values <.05). In electric lighting among cyclists the attitude and subjective norm towards cycling became more favourable (all p-values <.05).

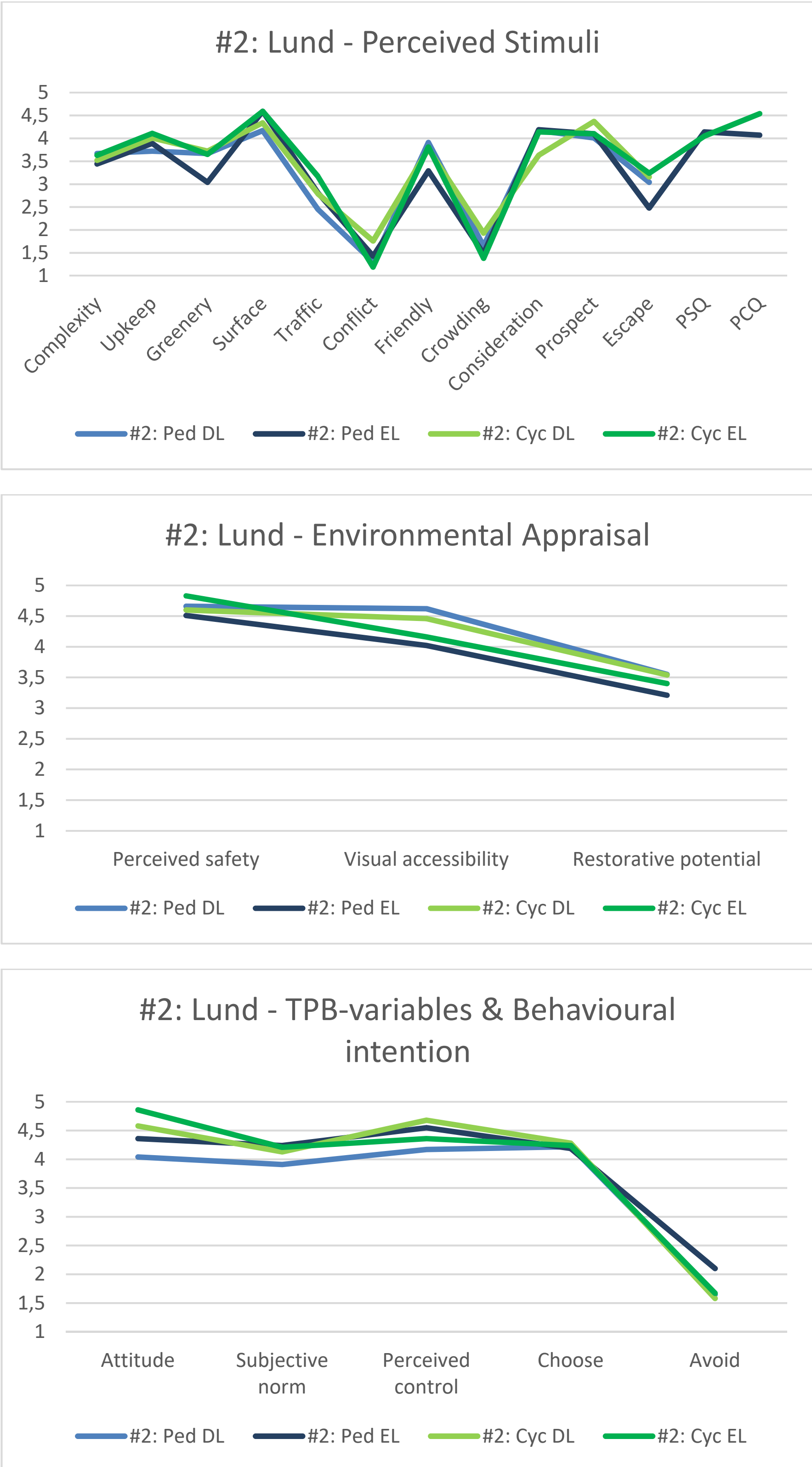


Figure 31. Lund Study 2: Mean values for participants' (pedestrians and cyclists) assessments of perceived stimuli, environmental appraisals, variables from Theory of Planned Behaviour (TPB) and self-reported intention to choose and avoid the path. DL – daylight, EL – electric light.

Effects of interventions on behaviour: speed and slalom

Pedestrians

Table 12 displays the outcomes of the analysis conducted to test the effects of the interventions on pedestrians' movement at both locations (for more details about the analyses refer to Yastremska-Kravchenko et al. 2024a).

The results suggest that both changes in the physical environment and lighting conditions have significant effects on pedestrian speed and slalom performance, with variations observed between the two locations. Additionally, there are significant interaction effects between these factors in Linköping for the speed, but not in Lund.

In Linköping, no statistically significant differences could be identified between pedestrians' in speed and slalom profiles in daylight between Baseline, Study 2 and Study 3. Neither did Baseline and Study 1 differ under electrical lighting conditions when only the lay out and surface was changed. However, in the comparison between Study 2 and Study 3 under electric lighting (with a change in lighting application in between), a decrease in both speed, and slalom, were observed. When comparing lighting conditions in general (daylight to electrical lighting), it appeared that during the Baseline and Study 2 data under electrical lighting, pedestrian speed was higher. However, after the change in lighting application (Study 3), the speed trend under electrical lighting became similar to the daylight trend.

In Lund, a statistically significant difference can be observed between pedestrian behaviour in terms of both speed and slalom during the transition from Baseline to Study 2 under electrical lighting conditions. However, the impact of changes in path layout and surface on these two variables (which could be analysed during daylight conditions from the same transition) was not statistically significant. Pedestrians also moved faster under electrical lighting conditions in both periods, but they deviated less after the lighting application was changed.

Table 12. Overivew of results for pedestrians' movements

Site	Group1	Group2	Change	DV	Significant effect
Linköping	Linköping_Baseline (DL)	Linköping_ Baseline (EL)	DL to EL	Speed	yes
				Slalom	yes
	Linköping_ Baseline (DL)	Linköping2 (DL)	Pavement (appearance of the separation lane)	Speed	no
				Slalom	no
	Linköping_ Baseline (EL)	Linköping2 (EL)	Pavement (appearance of the separation lane)	Speed	no
				Slalom	no
	Linköping2 (DL)	Linköping2 (EL)	DL to EL	Speed	yes
				Slalom	yes
	Linköping2 (DL)	Linköping3 (DL)	No changes	Speed	no
				Slalom	no
	Linköping2 (EL)	Linköping3 (EL)	EL application	Speed	yes
				Slalom	yes
	Linköping3 (DL)	Linköping3 (EL)	DL to EL	Speed	no
				Slalom	no
Lund	Lund_ Baseline (DL)	Lund_ Baseline (EL)	Daylight to EL	Speed	yes
				Slalom	no
	Lund_ Baseline (DL)	Lund2 (DL)	Pavement	Speed	no
				Slalom	no
	Lund_ Baseline (EL)	Lund2 (EL)	Pavement & EL application	Speed	yes
				Slalom	yes
	Lund2 (DL)	Lund2 (EL)	Daylight to EL	Speed	yes
				Slalom	no

* 'yes' values are marked in green to indicate an increase (Group1 < Group2), while they are marked in red to indicate a decrease (Group1 > Group2).

Cyclists

The results for cyclists at both locations are presented in Table 13. The results suggest that the interventions in physical environment and lighting condition in general have a statistically significant effect on speed and slalom.

However, a statistically significant interaction effect between these factors was found in Linköping only, and was associated solely with speed. This suggests that the relationship between speed and at least one of the factors changes depending on the level of the other factor. There is no statistically significant interaction effect between changes in the physical environment of the path and general lighting conditions on slalom at either location.

In the transition from Linköping Baseline to Study 2 following a change in layout and surfacing of the path (but not electric lighting), we observed an increase in cycle speed during daylight, accompanied by a decrease in slalom. However, this significance was not observed under electrical lighting conditions.

It is interesting to note that while no changes were observed in the speed and slalom profiles of movements during daylight between Study 2 and Study 3 (when daylight conditions remained the same), there was an increase in speed and a decrease in slalom during dark hours when the electric lighting was replaced. The comparison of lighting conditions for Study 3 in general, daylight and electrical lighting, suggests that speed profiles were similar, but slalom decreased.

In Lund, both speed and slalom show significant differences between the Lund Baseline and Study 2, suggesting an increase in speed and a decrease in slalom. However, according to the results, when we compare lighting conditions in general from daylight to electrical lighting, only for Lund Baseline speed profiles were significantly different between groups of cyclists, indicating that cyclists moved faster during daylight hours.

Table 13. Overview of results for cyclists' movements

<table>
<tr><th>City</th><th>Group1</th><th>Group2</th><th>Change</th><th>DV</th><th>Significant effect</th></tr>
<tr><td rowspan="14">Linköping</td><td rowspan="2">Linköping_Baseline (Daylight)</td><td rowspan="2">Linköping_ Baseline (EL)</td><td rowspan="2">Daylight to EL</td><td>Speed</td><td>yes</td></tr>
<tr><td>Slalom</td><td>yes</td></tr>
<tr><td rowspan="2">Linköping_Baseline (Daylight)</td><td rowspan="2">Linköping2 (Daylight)</td><td rowspan="2">Pavement (appearance of the separation lane)</td><td>Speed</td><td>yes</td></tr>
<tr><td>Slalom</td><td>yes</td></tr>
<tr><td rowspan="2">Linköping_ Baseline (EL)</td><td rowspan="2">Linköping2 (EL)</td><td rowspan="2">Pavement (appearance of the separation lane)</td><td>Speed</td><td>no</td></tr>
<tr><td>Slalom</td><td>no</td></tr>
<tr><td rowspan="2">Linköping2 (Daylight)</td><td rowspan="2">Linköping2 (EL)</td><td rowspan="2">Daylight to EL</td><td>Speed</td><td>yes</td></tr>
<tr><td>Slalom</td><td>no</td></tr>
<tr><td rowspan="2">Linköping2 (Daylight)</td><td rowspan="2">Linköping3 (Daylight)</td><td rowspan="2">No changes</td><td>Speed</td><td>no</td></tr>
<tr><td>Slalom</td><td>no</td></tr>
<tr><td rowspan="2">Linköping2 (EL)</td><td rowspan="2">Linköping3 (EL)</td><td rowspan="2">EL application</td><td>Speed</td><td>yes</td></tr>
<tr><td>Slalom</td><td>yes</td></tr>
<tr><td rowspan="2">Linköping3 (Daylight)</td><td rowspan="2">Linköping3 (EL)</td><td rowspan="2">Daylight to EL</td><td>Speed</td><td>no</td></tr>
<tr><td>Slalom</td><td>yes</td></tr>
<tr><td rowspan="8">Lund</td><td rowspan="2">Lund_ Baseline (Daylight)</td><td rowspan="2">Lund_ Baseline (EL)</td><td rowspan="2">Daylight to EL</td><td>Speed</td><td>yes</td></tr>
<tr><td>Slalom</td><td>no</td></tr>
<tr><td rowspan="2">Lund_ Baseline (Daylight)</td><td rowspan="2">Lund2 (Daylight)</td><td rowspan="2">Pavement</td><td>Speed</td><td>yes</td></tr>
<tr><td>Slalom</td><td>yes</td></tr>
<tr><td rowspan="2">Lund_ Baseline (EL)</td><td rowspan="2">Lund2 (EL)</td><td rowspan="2">Pavement & EL application</td><td>Speed</td><td>yes</td></tr>
<tr><td>Slalom</td><td>yes</td></tr>
<tr><td rowspan="2">Lund2 (Daylight)</td><td rowspan="2">Lund2 (EL)</td><td rowspan="2">Daylight to EL</td><td>Speed</td><td>no</td></tr>
<tr><td>Slalom</td><td>no</td></tr>
</table>

* 'yes' values are marked in green to indicate an increase (Group1 < Group2), while they are marked in red to indicate a decrease (Group1 > Group2).

A note on the BELYSA-workshop on lighting for pedestrians and cyclists

The BELYSA-project invited together with Cykelcentrum at VTI to an online workshop on lighting for pedestrians and cyclists in October 2020. The workshop aimed at sharing and discussing the first results from the baseline study and to gain insights from practice for the further development of the interventions and the project at large.

The workshop covered three main themes, environmental experiences and design, measurement of walk and cycle paths from a user perspective, and pedestrian and cyclist microscopic movement. Each theme was arranged as a short overview of research results and followed by break-out groups and discussions. The workshop attracted approximately 50 participants representing amongst others municipalities across the country, authorities such as Trafikverket, and organisations for example Cykelfrämjandet.

Discussion content evolved around:

Planning, design and maintenance of cycle and foot paths:

a) the need to define cyclists as a heterogen group has broaden during recent years with regard to the vehicle e.g. e-bikes, and cargobikes of different speeds and need of space setting new demands on infrastructure.
b) planning and design for developing a hierarchical structure of cycle paths – main routes - direct, overview (not secluded), scenic routes,
c) challenges with shared spaces with pedestrians including the feasibility of separating with painted lines, width required for flow and speed, navigation between small obstacles and different requirements on the electric lighting.
d) greenery as a restorative quality during daylight conditions, but associated with decreased safety and security during dark conditions increases need of maintenance.
e) development of infrastructure and need of maintenance during the winter season

Surface, risks and maintenance:

a) the importance of maintenance to avoid potholes that collect water and freeze,
b) where and when ice and grit is a risk for cyclists and pedestrians respectively,
c) and in relation to surface issues, the calibration of the measurement trailer from a cyclist perspective,
d) weather and seasonal effects of measurements.

Lighting, and environmental factors:

a) Standards for electric lighting for cyclists and pedestrians should be based on their needs (rather than the needs of motorised vehicles)
b) The role of ambient light for reassurance
c) Glare and shadows as risks

d) Turned off light as risk of accidents
e) Light pollution
f) Topography, air quality and noise.

Safety and security:
a) Important to consider design features that may constitute a risk in a crash, (light) poles, tree trunks etc.
b) Cycle routes with stop that requires one to stand still may be perceived as less safe at night time.
c) Cycle paths should be close to residential areas to be safe, more ”eyes” on the path.

The workshop topics of discussion confirmed the relevance of the BELYSA-project for practice. The group discussions especially helped us to be explicit in our intended target group i.e. pedestrians and cyclists as commuters and analysing the selected paths as they would serve as main routes. The discussion also drew our attention to the role of the midpoint of shared paths, and inspired the idea on slalom behaviour. Additionally the discussions provided insight and context to the practial challenges in planning, designing and maintaining cycle and foot paths of high quality all year around.

Discussion and conclusions

In the Nordic context, the seasonal variation provides very different conditions for pedestrian and cyclist commuters over the year. Especially the dark season could be a challenge with regard to not only temperature and precipitation, but also for perceived safety, security and comfort. It is argued that careful environmental design amongst others in terms of the provision and quality of electric lighting could contribute to extend the feasibility of walking and cycling across seasons (Bergström & Magnusson, 2002).

To this end, the BELYSA-project set out to improve the quality of travel for pedestrians and cyclists during dark hours. More specifically the project developed an integrated multidisciplinary theoretical and methodological approach to assess pedestrian and bicycle traffic with focus on micro-level environmental factors, involving objective quality-of-trip measures in daylight and electric light conditions. This integrated approach was used to evaluate the combined effect of micro-level environmental factors on pedestrians' and cyclists' experiences and behaviour.

Considering that previous research analysing environmental planning and design for sustainable travel has either focused on pedestrians or cyclists, a major contribution of the BELYSA-project is the parallel comparisons of pedestrian and cyclist environmental experiences and behaviour. We find that the two groups to some extent differ in how they perceive environmental stimuli and how they conceptually appraise (e.g. the integrated understanding of the place) the combined walking and cycling paths analysed in both Linköping and Lund. Moreover, we find strong indications that these groups by their microscopic behaviour respond differently to the environmental interventions introduced at both sites. A safe conclusion is that urban planning and design should not treat cyclists and pedestrians as a homogenous group, but rather make distinctions between them in analysising the needs for these two groups.

Our baseline for the OBEAs also reveal main effects of location and daylight versus electric light conditions, as well as several interaction effects (Table 5). Significant differences between the two locations come as no surprise. These differences should be interpreted as a support of the face validity of the self-report instruments. The effects of lighting condition on visual accessibility also seems reasonable, whereas the effect on traffic environment could be an artefact of the time of day and the daily changes in traffic flow. The perceived restorative potential came through as higher in daylight than in electric lighting conditions. This assessment is highly associated with the perceived presence of greenery and it might be that the greenery in current electric lighting is less visible or interpreted as a potential threating environment. In fact, other research has shown that purposefully lighting greenery may increase the perceived restorative qualities of a place (Nikunen & Korpela, 2009; Henning et al., in manuscript). The identified main effects and interaction effects of lighting conditions supports that perceptions and appraisals of pedestrian and cycle paths should be attended to taking into consideration diurnal and seasonal variation in daylight. This is also evident in the analyses of the interventions as some effects such as for perceived upkeep differed between daylight and electric lighting further described below.

In a practical perspective, municipalities often combine environmental interventions in their maintenance with the aim to improve safety, security and/or comfort. This was represented in BELYSA. In the original design a stepwise procedure was planned for, and this could be achieved in Linköping where the layout and surface of the path was first subject to change, and then in a second step the electric lighting was changed. Due to unforeseen problems with a new type of surface layer in Lund these interventions where not possible to separate. However, our results from both TEA and OBEA nicely show how in Linköping the measures and assessments related to the design of the path significantly change in the first post-test. In the OBEA, assesments of upkeep and surface was consistently significantly higher than at baseline. Moreover, the cyclists assessed complexity to be higher after this first part of the intervention. One reason may be that the white line that was added to separate between pedestrian and cyclists as well as the road marking symbols generated more information to process increasing, the mental load for cyclists although at the same time improving perceived traffic safety. Unexpectedly also the presence and quality of greenery was assessed as higher. A likely explanation may be slight differences in weather conditions and in foliage of the trees between the two data collections (Figure 22).

Figure 22. Differences of foliage of the trees between the first (October 13th, 2021) and second (November 10th, 2022) post-test in Linköping.

Notably for the group of cyclists the perceived strength quality of the light significantly decreased. This could to some extent be attributed to the lower illuminance, with $\bar{E}$ being 11,87 lx compared to 14,87 lx in baseline and E_{min} 0,50 lx compared to 2,2 lx, mainly due to the foliage of the trees shading the pedestrian and cycle path at the first post-test. This can also be explained by the new black asphalt having lower reflectance than the original thereby creating a less luminous environment. Taken together these results go hand in hand with the cyclists' increase in speed during daylight but not in electric lighting conditions. The favourable attitude towards cycling was significantly strengthened. However, no effects could be identified in the conceptual environmental appraisals. It seems like the interventions did not change the overarching impression of the place for neither pedestrians nor cyclists.

In the second post-test, the assessments of upkeep and greenery significantly decreased. The change in perceived upkeep could to some extent be explained by that the asphalt had been somewhat worn after a year. But the main reason is likely related to the weather conditions as it had been raining resulting in a wet surface more often during data collections and it was also leaves on the ground. As for greenery the explanation is similar as above, the challenge of keeping seasonal variation constant across years, this is also relevant for the decrease in perceived restorative potential among pedestrians during daytime. Considering that the new lighting was introduced at this stage, it seems reasonable that the assessment of perceived strength quality has increased, and that this gave a more arousing experience. From an energy use perspective, this is interesting since the illuminance level ($\bar{E}$) was lower, but the uniformity and E_{min} higher as seen by TEA. However, the new electric lighting was assessed as lower in perceived comfort quality than the previous lighting, this self-report scale amongst other involves glare and colour temperature. Indeed the CCT was higher, going more in the direction towards blue than the original light source. The result may explain why the perceived visual accessibility despite the higher perceived strength quality did not increase. Still the cyclists expressed an increase in safety, speed and reduced slalom, all aspects supportive of a better cycling environment. The pedestrians expressed a decrease in speed and slalom, and a stronger intention to walk along the path.

In-depth analyses of the microscopic behaviour also suggest that the separation between cyclists and pedestrians, indicated by a white line and road marking symbols in Linköping, helped to keep path users' trajectories straight, so the slalom decreased. Moreover, the results of microscopic behavior analysis conducted for the latest intervention in Linköping revealed a decreasing difference in speed trends among path users between daylight and electric lighting conditions. Assuming daylight speeds as the 'desired' choice, this latest intervention in Linköping may be seen as an improvement for path user perception. Still, further research is needed to provide recommendations for an 'optimal' design solution. For example, using two different textures (e.g. asphalt vs. concete tiles) are known to be more effective in making pedestrians and cyclists to 'keep to their share of the path (SKL, 2010). Most probable, such evaluations were done in daytime only, thus the effects might differ under electic illumination under which the visual properties of the two surfaces might be quite different.

In Lund the effect of the new asphalt surface, the slightly trimmed greenery and the newly added light source were assessed at the same time. Consequently, the post-test 1 yielded results for the complete environmental intervention. Similar to Linköping post-test 1 significant increases were identified for upkeep and surface, and Linköping post-test 2 significant increases in the perceived lighting quality could be identified. The perceived strength quality was considered improved by both pedestrians and cyclists, whereas the perceived comfort quality was considered improved by cyclists, but the assessments stayed the same among pedestrians. This pattern is inline with a parallell increase in assessments of perceived visual accessiblity and safety among pedestrians (Johansson et al., 2014). Among cyclists the attitude and subjective norm towards cycling became more favourable. The pattern of changes in microscopic behaviour identified in Linköping was repeated in Lund. The pedestrians reduced their walking speed and slalom, whereas cyclists increased speed and reduced slalom from before to after the intervention.

The consistent pattern of reduced speed among the pedestrians may seem contradictory, but it could be interpreted as an indication that the environment is appreciated and that there is no reason to speed through the place (Franěk, 2012). As for the social aspects of the environment, no changes were identified for Linköping despite that a new painted white line could be expected to reduce conflicts between pedestrians and cyclists. On the other hand, this clear division of the pedestrian and cyclist share of the path made the dedicated width for each user group more narrow, and likely forced pedestrian-pedestrian and cyclist-cyclist closer to each other.

In Lund significant effects on the social aspects could be identified during electric lighting conditions. Conflicts were perceived to be reduced as well as crowding, but so was friendliness. The social aspects are only partly dependent on the physical design and partly on other people that happen to be at the site during data collection. Therefore, it is challenging to interpret the results for the social dimensions as these results are also sensitive to how many other persons were around and how they acted.

Theoretical advancements

Theoretically the BELYSA project has advanced research on electric lighting conditions for pedestrians and cyclists in two important ways.
First, using the Brunswick model, we theoretically integrated research on sustainable urban mobility, and electric lighting. In these fields many perceived features and qualities important for walking and cycling have been discussed, but separately without any conceptual linkages or hierarchy. The conceptual model proposes how TEA and OBEA should be linked as well as how OBEA of perceived stimuli should be linked to OBEA of the integrated environmental experiences the conceptual environmental appraisals. The framework helps to link research on the role of people's experience of urban planning and design – environmental perception with social-psychological perspectives focusing on people's attitudes to understand behavioural intentions.

Secondly, we have advanced the understanding of pedestrian and cyclist microscopic behaviour by introducing the concept of slalom to capture deviations from the straight (most efficient) travelling path. Previous research on pedestrian and cyclist behaviour in field has, drawing on research of motor vechicles, largely focused on flow and speed ((Fotios et al., 2019; Pedersen & Johansson, 2018; Painter, 1996). Narrowing the focus towards individual behaviour helped to understand how people adapt their behaviour in response to specific features (perceived stimuli) and the presence of other people. Here the analysis of slalom have implications for the directedness and easiness of the trip. It is crucial to acknowledge our assumptions regarding the interpretation of the slalom measure. The notion of a 'desired slalom' can vary depending on the type of path users, purpose of the trip as well as the geographical location of paths. When comparing commuters or those with job-to-do (e.g., couriers) with tourists or recreational cyclists/walkers, we assume that under 'ideal' physical environmental conditions perceived on a path, the first group would prioritize efficiency by maintaining a straight trajectory to reach their destination as fast as possible. Conversely, under identical conditions on the path, the latter group might purposefully deviate from a straight path to engage with the urban environment or simply enjoy the journey. For the BELYSA the selection of study sites adhered to a specific criterion: paths frequently used for walking or cycling commuting between the city outskirts and the city center. Therefore, we consider slalom within the context of a commuting route and posit that a decrease in slalom signifies a perceived improvement in the pathway by path users.

Methodological strengths and challenges

The unique multidisciplinary approach we employed to combine competences and methods helped to explain how the interventions changed the environment both from a measured, experiential and behavioural point of view. The integrated approach also points to the challenge of detail and scale. The walk and cycle paths investigated were approximately 200 meters. This distance has previously been shown to be feasible for the structured walk with self-reports (Johansson et al., 2016; Johansson & Pedersen, 2019? Ekosystem). However, paths where straight without complex traffic situations, this meant that the distance may have been too short to capture variation in the microscopic behaviour (e.g. interactions between the road users on crossing courses or combination of interactions and changes in the geometry of the path, e.g. a turn or a narrowing). On the other hand, for the bicycle measurement trailer developed to collect fine-grained environmental information, the 200 metres distance yielded a very large amount of data difficult to manage. In the end, the data collected could be combined, but for further research it is advisable to save effort by initially define the appropriate environmental scale to be analysed. In addition, the timing of the measurements must be considered. Performing laser measurements with the BMT during autumn when the structured walks were conducted was not optimal due to the sensitivity of the instruments for temperature, surface wetness, leaves and other debris. Road condition measurement are preferably done during summer season.

Our integrated approach is expected to benefit from further technological advancements such as 3D scanning. The basic idea of the measurement trailer was to simultaneously obtain measures on several environmental factors, such as illuminance levels, noise and surface quality in a convenient way. The complexity of the system made it very fragile and required complementary on-site measures.

Similarly, the analysis of the trajectories would benefit from further technological developments. In the BELYSA project the trajectories were produced using a semi-automated tool, meaning that significant amount of work was performed manually. As a result, although the project generated many hours of video recordings, the sample sizes in some groups was still small. In particular, the repetitive and relatively straightforward tasks of stabilizing and calibrating each 20-minutes video clip should be further automated. Employing enhanced calibration markings (reflective or emitting own light during a short period prior to the experiment start) would allow for their automated detection (rather than an operator searching a clicking each point manually). While automated road user detection and tracking tools are available today, the initial tests revealed that they do not perform particularly well with our footage due to low resolution (and differences in brightness (especially in the dark) between a person and the background. Using thermal cameras would have help to both distinguish between people and the environment, but also eliminate all issues related to personal data protection. For example, it would be possible to fly the drone at a lower height (thus increasing the size of each persons in the video) without risking of collecting any other information that would allow to recognize them. At the moment of report writing, there are no 'off-the-shelf' and affordably priced drone solutions with a thermal sensor available. We might expect the situation to change in the future.

An important aspect of applied research conducted in real world settings rather than in laboratories is to establish a high degree of so called ecological validity of the study, that the results hold bearings for real environments (rather than laboratory settings or simulated environments). The structured walks have been shown to be a useful method to assess people's environmental perceptions and appraisals. However having a researcher on-site, and being instructed on how and where to walk or cycle likely affect the behaviour. The behaviour observed in the video recordings of the participants may therefore not be fully representative. At the baseline data collection, video recordings were also made of pedestrians and cyclists who were not invited to the study. Some deviations were also identified between these two groups, suggesting that observations of pedestrians and cyclists under regular/naturalistic conditions give a broader picture of what behaviour could be expected along a certain path. However, we know little about their purpose and experience.

Further applications of the methodological approach

In the BELYSA-project extensive efforts were made with regard to the theoretical and methodological approach. The practical experiences and learnings have greatly inspired further research in multidisciplinary collaborations. The theoretical framework and the questionnaire developed for the observer-based assessments are currently used in the NorDark-project – a collaboration with Uppsala in Sweden and Ålesund in Norway aiming towards sustainable lighting solutions for walking paths in urban forests (Johansson et al., 2024; Tsiakiris et al., in manuscript). The research has also been extended to address electric lighting from a child perspective (Litsmark et al., 2023). The combination of observer-based environmental assessment and behavioural observations by drones have been further advanced in ongoing research on the flow of alighting and boarding passengers of commuter trains (Kuipers et al., 2024).

In on-going research conducted at VTI we are developing measuring methods more suitable for cycle paths and are also trying to define metrics and limit values describing surface evenness that are related to the comfort of cyclists and could be used, for example, in contract performance control of newly built cycle path surfaces. The development of the BMT is one important component in the aspiration to achive this goal. This research is financed by the Swedish Transport Administration and conducted in cooperation with Ramboll Sweden AB. The development of the BMT and the lessons learn perfoming the measurements in the BELYSA project has also been beneficial for an on-going PhD project with the aim to improve the knowledge of the degradation factors of cycle paths and thereby enhance the maintenance efficiency of cycle paths (Larsson et al., 2022 and 2023).

Future research should preferably also include new forms of transport modes for example e-bikes, cargo-bikes and e-scooters these modes differ in speed and need of space. Furthermore it would be worthwhile to directly analyse experiences and micro-scopic behaviour in relation to traffic safety and risk of accidents.

Contribution to an energy efficient transportation

A development towards more sustainable travel calls for improvements in infrastructure for pedestrians and cyclists. The BELYSA project has shown that it is essential to consider different user groups, seasons and times of day if to reach the full potential of urban planning and design for a shift towards sustainable travel. This means that improvements must be valid for both pedestrians and cyclists and during daylight and dark hours.

Our results indicate that it is more important with a high uniformity and minimum illuminance (E_{min}) rather than a high mean illuminance level ($\bar{E}$). From an energy use perspective this is interesting since more energy efficient light sources such as LED-lighting might give good enough lighting conditions for pedestrians and cyclists. However, since the colour temperature seems to be important for the perceived comfort quality, further development of energy efficient lighting sources should aim to find solutions that also but a more pleasant lighting colour. Further research is needed to optimise electric lighting for pedestrians and cyclists respectively.

Currently the development of cycle and pedesrian paths in Sweden largely relies on practice-based experiences. Systematic evaluation and documentation of what works and what doesn’t are lacking. The theoretical framework and associated methodological developments provide a sound base for building evidence-based knowledge on shared walking and cycling paths. The theoretical framework could guide the choice of variables for technical measure and observer-based assessments to secure that they are aligned. The procedures and methods developed facilitate comparisons of evaluations across cases. Here it should be stressed that it is important to consider several environmental factors as they interact in the overarching conceptual environmental appraisals.

The outcomes of the two case studies in Linköping and Lund respectively suggest that evaluations should be carried out for both pedestrians and cyclists as these groups tend to differ in their sensitivity to different environmental factors and appraisals. While the case-study results strongly indicate that upgrading of surface and lighting are important to support sustainable travel, further research in more controlled laboratory studies would be needed to establish the most efficient designs.

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Appendices

Administrative form

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