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Drivers' Experiences and Informed Opinions of Presence Sensitive Lighting Point towards the Feasibility of Introducing Adaptive Lighting in Roadway Contexts

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Abstract: Applications of adaptive and intelligent lighting technologies such as presence sensitive lighting, potentially offer solutions for reducing the energy consumption of road lighting while maintaining user comfort and safety. However, little is known about road users' experiences of such lighting. To address this gap, we conducted a real-world case study of a presence sensitive roadway lighting on a collector road in a housing area in southern Finland. New, controllable LED lighting with PIR (passive infrared) presence sensors was implemented along the road, and test scenarios were designed, programmed, and tested. The lighting was adapted both to motor vehicles using the road and to the measured traffic density along it. Drivers' experiences and attitudes toward the lighting were collected in a three-phase evaluation with questionnaires from the community of about 1000 households using the road as part of their daily mobility. The results indicate that as an experience, presence sensitive lighting in a road environment was at least as positive as traditional, uncontrolled lighting. User experiences of presence sensitive lighting did not differ from the experiences of uncontrolled lighting regarding pleasantness, uniformity, glare, and road visibility. Most of the drivers (86%) did not notice any dynamic change in the lighting. When informed about the tested lighting strategies, most of the participants (72%) would prefer either one of the intelligent lighting modes to be the permanent lighting solution. The results of this exploratory, real-world study point towards the potential feasibility of this technology from a user experience perspective, as the experienced stability of the lighting was unaltered in the tested scenarios; importantly, it also highlights the need to study adaptive roadway lighting further, especially through confirmatory studies in controlled settings.

Keywords: presence sensitive lighting; roadway lighting; drivers' experiences; user experience; evaluation; sustainability; adaptive lighting; intelligent lighting; smart cities; participation

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1. Introduction

There is a growing need to reduce the energy consumption of road lighting while maintaining user comfort and safety. Electric lighting is globally a significant energy consumer, even though exact consumption estimates vary in different publications. Around a decade ago, it was estimated that 3.19% of global electricity generation was used for lighting [1]. In Italy, for example, outdoor lighting represented 2.1% of the country's whole electric consumption [2,3]. Global electricity consumption altogether has been reported to be increasing by approximately 3% each year [4] and recent figures estimate even around 15–20% measures of global electricity consumption for lighting [5–8]. Furthermore, outdoor lighting devices are estimated to form 15–20% of global lighting consumption [9]. In Europe, the share of street lighting consumption is 1.6% of total electricity consumption [10,11].

In recent years, the amount of illuminated area and light radiation has been growing globally despite the change to LED with aims to save energy: in a study period from 2012 to 2016, Earth's artificially lit outdoor area grew by 2.2% per year, and the total radiance grew by 1.8% per year [12]. This brings up another critical aspect, besides energy consumption: the harmful effects of excess light on nature and people. The International Dark-Sky Association (IDA) defines light pollution as the inappropriate or excessive use of light, which includes "Glare—excessive brightness that causes visual discomfort, Skyglow—brightening of the night sky over inhabited areas, Light trespass—light falling where it is not intended or needed, [and] Clutter—bright, confusing and excessive groupings of light sources" [13]. In addition to the fact that more than 80% of the world population lives under light-polluted skies [14], light pollution has several negative impacts on wildlife and the ecosystem including loss of biodiversity, changed population structure, reduction in local populations and decreased ecosystem resilience [15,16]. For example, street lighting has been detected to disturb commuting bats, which are nocturnal animals [17]. The negative effects on humans include interference with sleep, increased stress response, and other health hazards [15].

Applications of adaptive and intelligent lighting technologies, which could be integrated into smart city strategies, potentially offer solutions for reducing both energy consumption and light pollution. However, there is still a lack of real-world research scrutinizing the experiences of drivers in adaptive and intelligent roadway lighting situations.

Thus, our research aimed to test and study presence sensitive roadway lighting in a housing area in Finland, and to evaluate drivers' experiences of and attitudes toward it. The study was part of the Sencity—Intelligent Lighting as a Service Platform for Innovative Cities project. The project piloted smart lighting solutions in six Finnish cities in different kinds of urban environments. The research had three focus areas: (1) to study user needs and user experiences of intelligent lighting, (2) to develop and test sensing, data analysis, and communication methods and technologies needed for the user-centric designs, and (3) to generate business opportunities for smart, data-based services. In the pilots, the aim was to employ lighting infrastructure as a service platform—an Internet of Things backbone—in a smart city. Together, separate pilots in different cities around Finland created a living lab ecosystem for developing and testing innovative solutions. The Sencity project group consisted of collaborating research institutions, cities, and companies in the fields of lighting and ICT [18].

In the following, relevant viewpoints and findings of recent research are presented and discussed to give background for the study. These include the studies of adaptive and presence sensitive lighting and the evaluation of experiences of such environments; user aspects of roadway lighting; and concepts relating to sustainability in smart cities. At the end of the chapter, the aims and research questions of the study are presented.

1.1. Conceptualizing Adaptive and Presence Sensitive Lighting

Technically, the concept of adaptive lighting refers to an intelligent lighting system, which is equipped with sensors and actuators that allow the system to dynamically adapt to the current conditions or to the needs of individual users [19]. Adaptation in lighting systems can be achieved through sensor networks that gather information from the environment, such as the flow of traffic, and feed it to a closed-loop adaptive system. One example of adaptive systems is the presence sensitive roadway lighting, i.e., lighting that is programmed to adapt to the presence of vehicles or people. A driving force for systems development has been the potential of this adaptive behaviour to offer energy savings and cost efficiency [20,21]. At the moment, most of the previous studies concerning adaptive lighting concentrate on either the technological solutions of different elements of adaptive lighting systems, such as sensors and algorithms [22,23] or the demonstration of the energy saving potential through simulations [24–26] and in real-world case studies [23,27–29], although there are exceptions, as well [30–32].

In our research, however, we have integrated users' experience and designers' input into a concept of adaptive system as important elements influencing the system behaviour and outcome, as presented in Figure 1. Thus, "adaptive lighting can be seen as an adaptive system, where environmental and user-related data are fed into and processed according to the rules created by a designer. This results in output control commands to luminaires of the system, which behave accordingly, thus creating a lighting environment. This creates an experience for users and may influence their behaviour, which may again affect the lighting behaviour" [33] (p. 16).

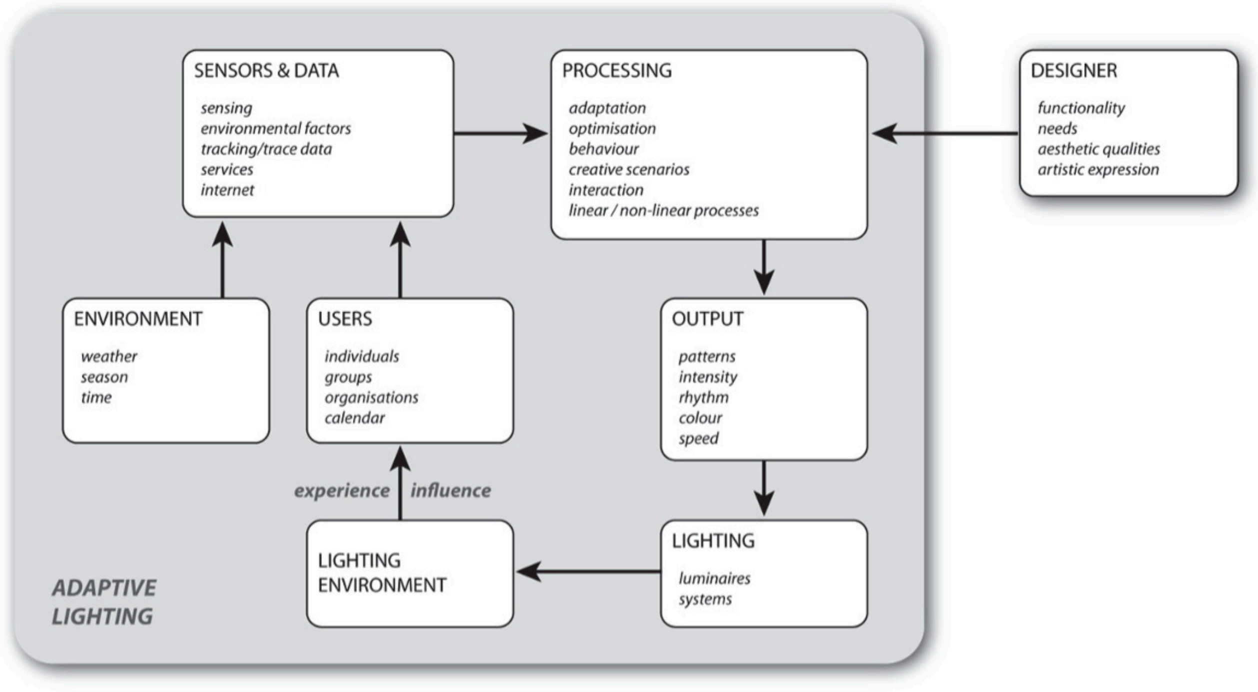

Figure 1. Adaptive lighting conceptualised as an adaptive system. Figure © Henrika Pihlajaniemi and Toni Österlund.

Generally, in our research activities, we have conceptualised adaptive lighting as a design task, developed processes and methods for designing [33,34] and evaluating [35,36] adaptive lighting, and scrutinised multifaceted users' experiences in different real-world contexts, such as urban parks and light-traffic routes [7,37].

A few other recent studies can be found with scope outside of technology or energy aspects. The design process and methods and social adaptation have been the focus of studies by Magielse [38]. Users' experiences of environments lit by adaptive lighting are explored in only a few research publications. For example, in an outdoor lighting context, research has been concerned with the effects of adaptive lighting on perceptions of safety [39] and defusing escalation of aggressive behaviour [40], and, in an interior lighting context, the influence of the light spectrum on sleep rhythm of elderly people [32].

As adaptive lighting is still a rather new element in urban and other outdoor environments, there is still a lack of research scrutinizing users' experiences in such environments. Most of the studies available are from pilot installations, built for experimental research purposes and situated in areas and routes meant for pedestrians and light traffic. A study from 2011 by Atıcı et al. [41] focused on a pedestrian setting, noting that other forms of mobility, such as cycling and automobility, should also be analysed.

1.2. Safety and Other User Aspects of Roadway Lighting

Even though no previous studies of experiences of presence sensitive roadway lighting can be found, there are a variety of studies and literature on user aspects and design factors of traditional—i.e., non-adaptive—roadway lighting, which can be referred to here to give background to this study.

Although lighting may have negative impacts on nature and the ecosystem through light pollution, energy consumption, and CO_2 emissions, there is a general understanding based on research that it is economically and socially valuable to illuminate roads. The benefits of road lighting and the reasons to illuminate roadways during dark periods include the following aspects: prevention of traffic accidents and promotion of traffic safety; ease of passage for all road users; a comfortable driving experience as a visual task; helping to reduce crime and the fear of crime; and enhancing the nocturnal image of cities and towns contributing to the commercial and social use [42–45].

The influence of road lighting on reducing the amount of traffic accidents has been well documented; for example during the energy crisis of the 1970's when several studies were conducted evaluating the impact of the presence or absence of roadway lighting [44]. A literary review conducted in Sweden [45] presents a collection of more recent studies of accident statistics. The review had a focus on urban areas, not rural ones. Based on their review, the authors summarise that in urban areas, pedestrians are at a heightened risk of having an accident in darkness when compared to a daylight situation, the risk being the greatest with unilluminated roads. In addition, bicyclists may be at an increased risk in darkness, but they found no obvious increase in the risk of accidents involving only one or more motor vehicles in darkness when the effect of other factors such as alcohol and drowsiness was controlled for. However, the authors point out that conclusions from different studies are not completely in agreement concerning the risk for car drivers.

The parameters of lighting standards guide the design of road illumination ensuring the lighting quality for drivers. The relevant factors are visual performance, governed by average luminance (LAv), overall uniformity of luminance (Uo) and disability glare (TI), and visual comfort, being the function of average luminance (LAv) and longitudinal uniformity of luminance (UL). Discomfort glare (TI) has an effect, as well, which is controlled to some extent in the design process with the factor discomfort glare (TI) [42]. The two types of glare are frequently experienced while driving at night. Disability glare deteriorates visual performance causing reduced contrast sensitivity and due to the scattering of bright light within the eye. Discomfort glare is the subjective sensation of glare, which can be present without lessening visual performance [45]. The suitability of these parameters and the existing way of specifying road lighting for drivers, which are based on studies conducted decades ago, has been questioned by Raynham [42], and new research is needed especially due to the introduction of adaptive lighting technologies. In Italy, a national standard (UNI 11248/2016) already considers the need for dynamic lighting levels. It allows reducing light levels by up to 4 classes (e.g., from M1 to M5 or from M2 to M6) in periods when the traffic flow is expected to be lower [11].

Through analysing the visual needs for driving—the detection of pedestrians and possible obstacles and the ability to steer a vehicle—it has been hypothesised that there are two modes of vision relevant to driving: focal and guidance. Focal vision is needed for visual tasks involving acuity, contrast, and accommodation, while guidance vision is linked to the sensation of motion. Even though focal vision deteriorates at night, guidance vision remains highly efficient. Steering is suggested to depend heavily on guidance vision, whereas detection of pedestrians needs focal vision. Thus, the ability to steer a vehicle is not affected by darkness, which results in the driver not being aware of the reduced visibility, which increases the risk of accidents [45–47]. Recent research from Finland concerning dimmed road lighting in an urban road suggests that it is feasible, from the drivers' point of view, to reduce road lighting intensity when car headlights are used [48].

An interesting methodology for adaptive lighting based on the selection of a lighting level through the relationship between lighting and safety was presented in [44]. The presented approach was developed from the analysis of crashes and light levels on roadways. The adaptive lighting methodology can be implemented on the basis of traffic volumes, roadway design features, and other lighting issues—the needs of a driver. "For an adaptive lighting system, the light level requirements change on the basis of roadway conditions. The current approach calls for changes in the corresponding weighting factors as roadway conditions change, which determines a different lighting class and, therefore, a different required design level [44] (p. 27). Proposed design level selection criteria include speed, traffic volume, median, intersection or interchange density, ambient luminance, guidance, pedestrian-bicycle interaction, and parked vehicles [44]. The presented methodology can be seen as an example of the use of algorithms, which guide lighting conditions in an intelligent way within smart city contexts.

1.3. Adaptive Roadway Lighting as a Sustainable Smart City Research Focus

The development and application of adaptive roadway lighting into urban environments may be seen as an example of smart city development; this, we argue, is due to its focus on the use of digital and networked infrastructures to enable urban development and to improve efficiency, to borrow the description of [49]. However, there is no consensus on what constitutes smart city development. Overall, the research of smart cities and the smart city agenda is highly contested by researchers and scholars [49–53], even though various ad hoc definitions have been put forward. Importantly, these scholarly critics point out that the concept is highly intertwined with business-led interests, and is pushed by large technology companies [49,51–53]. The academic research on smart cities is also global and highly interdisciplinary and thus includes technology and business-focused approaches that highlight application-focused viewpoints deemed important by these fields. Thus, the lack of definition of the smart city concept may arguably be due to the difficulty of separating business strategy from research; and within research, the difficulty of integrating and balancing technology research, business research and development, and critical scholarship. For our purposes here, then, the use of digital and networked infrastructures in built environments is seen as a central feature of smart city development, as it fundamentally separates smart city development from other, non-digitally enabled urban development. Adaptive roadway lighting should arguably then be seen as a fundamental aspect of smart city research and development.

As stated, some of the research and development work on smart cities has been criticised for being overly technology and business oriented. This has led to oversight on at least two important fronts: issues of sustainability and civic participation [49,54]. For example, Ref. [54] identified a lack of connection between smart city definitions and sustainability issues, the major exception here being the European Smart Cities initiative, which does include sustainability in its definition of smartness [55]. Thus, there is still much work to be executed to bridge the gap between smart city development and sustainable urban development.

One of the major challenges of unifying smart cities and sustainability research interests is the lack of rigour in defining *both* central concepts. Sustainability is as hard to define as "smartness" is, and the origins of sustainability are also somewhat obscured. While the roots of sustainability can be traced back all the way to the 1700s, the contemporary use of the concept and the call for a sustainable society emerged only in the 1970s and has developed gradually into the wide-ranging, transdisciplinary discourse we see today. [56]. Thus, marrying the concepts of smartness and sustainability may give rise to even more weakly defined attempts at understanding the possibilities of creating sustainable smart cities. Yet sustainable urban development is an absolutely crucial goal for humanity. Indeed, "sustainable cities and communities" is one of the United Nations' 17 sustainability goals, as is "build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation" [57]. It is no wonder then, that the European Smart Cities initiative is placing increased emphasis on sustainability as an aspect of smart city development [55].

Sustainability is often conceptualised through the three metaphorical pillars of sustainability: ecological, social, and economic pillars that uphold sustainability as the overarching goal [56]. Applying these three pillars or aspects to the context of cities, Richardson [58] has defined sustainable urban development as "a process of change in the built environment which fosters economic development while conserving resources and promoting the health of the individual, the community, and the ecosystem" [58]. This is a definition that is suitably integrative for our purpose of studying adaptive roadway lighting. The successful implementation of such a technology as a part of roadway infrastructure must support all of these aspects, in short: conserving resources, improving individual and community health, and fostering economic benefits.

Recently, the concept of sustainable urban development has emerged as a topic of concern for smart city research and development, giving rise to the concept and research area of sustainable smart cities [59]. As this research is still in its infancy, much of this literature focuses on a few topics, for example, urban form and structure, mobility patterns, or household waste [59], which are fundamentally important urban issues. However, compared to the task of reforming urban structures, adaptive roadway lighting may represent a more readily applicable, low-hanging fruit for urban resource savings, as lighting infrastructure is already present in many built environments, and lighting fixtures must inevitably be replaced and updated due to wear and tear. Thus, adaptive lighting infrastructure has the potential to be a major area of interest for sustainable smart city research and development. However, this research is still largely unconnected to the sustainable smart city literature.

Adaptive roadway lighting may incur energy savings (cf. Introduction) on a global scale, and these savings may also translate into large economic savings for communities. Thus, from a smart urban development point of view, the largest challenge at hand in the research of adaptive roadway lighting is how this technology can be applied in a responsible, safe, and ethical manner, without compromising—and preferably improving—roadway users' experiences. As seen above, critical smart city literature urges the importance of stakeholder and citizen participation in this [49,51–53]. To this end, there is a need for more real-world, empirical, and participatory studies of road users' experiences with regard to adaptive roadway lighting. These experiences must be studied thoroughly in different geographical and cultural contexts, wherever adaptive roadway lighting is considered, and it must eventually include various levels of participation from user feedback to co-creative practices [60]. Indeed, this may yield benefits to smart city research and development as well, since adaptive lighting is such a visible, readily tangible part of urban infrastructure and a fundamental part of the urban and roadway experience. Thus, the participatory research of adaptive lighting may serve as an important practice-based laboratory for how to implement participatory research in smart city developments in general.

1.4. Aim of the Study

To address these gaps in knowledge, our research designed and studied presence sensitive roadway lighting in a housing area. The tested presence sensitive lighting method aimed to maintain the experienced stability of lighting around the road user, contrary to the present manner of dimming or even turning off lighting on the entire road in order to gain energy savings. The lighting that was tested in our study adapted both to motor vehicles using the road and to the measured traffic density along it, enabling us to evaluate drivers' experiences and attitudes concerning it. A traditional lighting scenario was also implemented, as we wanted to compare the user experiences of traditional and presence sensitive lighting. Our research questions were the following: How do drivers' experiences of presence sensitive roadway lighting compare to experiences of uncontrolled, traditional lighting in a real-world setting? What are the experiences, opinions, and attitudes of informed participants regarding a real-world implementation of two differing intelligently controlled lighting scenarios: presence sensitive lighting, and presence sensitive lighting based on the measurement of traffic density? How did participants experience participation in developing roadway lighting and gaining information about tested lighting solutions? The case study was conducted along a collector road in Salo, a town in southern Finland.

The results of this exploratory, real-world study point towards the potential feasibility of this technology from a user experience perspective, as the experienced stability of the lighting was unaltered in the tested scenarios; importantly, it also highlights the need to study adaptive roadway lighting further, especially through confirmatory studies in controlled settings.

2. Materials and Methods

In our study, which situates methodologically within the field of design research, we followed a mixed-methods approach [61,62], where quantitative data of drivers' experiences was combined with qualitative data of experiences and informed opinions. The study was a case study research in a real-world setting, which included the participation of local people. Our research approach was exploratory [63,64] in-the-wild research [65–67]. Exploratory studies aim to widen the scope of research by producing knowledge and insights about novel phenomena and, importantly, by uncovering new relevant research questions and hypotheses for further, confirmatory research. In-the-wild user studies operate in more naturalistic, real-world settings and aim to capture everyday life user experiences. The research procedure as a whole adhered to the guidelines for the responsible conduct of research (the RCR guidelines) which have been published by the Finnish National Board on Research Integrity TENK, appointed by the Ministry of Education and Culture in Finland [68].

2.1. Research Setting and Participation Process

Our case study consisted of a real-world test of presence sensitive roadway lighting, which adapts both to motor vehicles and to the measured traffic density along a collector road (Figure 2).

Figure 2. The map shows the collector road (Kalkkimäenrinne) test area in the context of the Tupuri housing area. The collector road had two-way traffic with one lane in each direction. The test area included one intersection, four T-junctions and six pedestrian crossings.

A new, controllable LED lighting with PIR (passive infrared) presence sensors was built along the road, 41 light poles altogether, and test scenarios were designed, programmed, and tested. The luminaire type was Easy LED PRO Flow S 30-850 UP-R 740, with luminaire wattage of 76.0 W, lumen output of 8470 lm, and correlated colour temperature of 4000 K. The mounting height was 10 m. The manufacturer of the presence sensor and intelligent lighting control system was Lumine. Users' experiences of the lighting were collected with questionnaires from the surrounding community of about 1000 households that use the road for daily mobility, and from other interested inhabitants of the city. The roadway was used only by cars; the light traffic route for pedestrians and cyclists was located separately in a surrounding forested area.

The study consisted of three scenarios, which tested three different lighting control methods (Figure 3). The first scenario ('traditional' lighting control method) ran from 23 January–5 February 2017. In this phase, the new lighting was controlled in a basic manner (daylight level-based control): during the bright period of the day, the lights were turned off, and during the dark period, they were on at a 100% control level. The sensor detected the threshold lux level and turned the lights on and off automatically. During the second scenario ('presence sensitive' lighting control method; 6 February–26 February 2017), a presence-based dynamic control was added to the previous basic daylight level-based control. In this phase, the lighting was controlled dynamically so that it was always brightened around a moving car to the maximum control level of 100%, and in those parts of the road where there was no traffic, it was dimmed down to a 20% control level. The dimming and brightening were executed softly using a 3 s ramp up and down. The bright area around a detected vehicle consisted of five streetlights: the one which detected the car with a passive infrared (PIR) sensor as well as two forward and two backward lights. In the third scenario ('presence and traffic density sensitive' lighting control method; from 6 March 2017 onward, questionnaire deployed 19 June–2 July 2017), a third control method was introduced to complement the two former ones. The introduced method was based on the measurement of traffic density: the lower control level of lighting adapted to the amount of traffic detected along the route. When traffic was dense, for example during the commute-heavy periods in the morning and in the evening, the control level of the lighting was dropped to 70% on those parts of the road where no traffic was detected. During times of moderate traffic, the level was 40%, and with the lowest traffic density during the night, the level dropped to 20%. The times of sunset and sunrise in Salo varied along the test period being on 23 January 16:16 and 09:03; on 6 February 16:53 and 08:30; on 6 March 18:07 and 07:11; and on 19 June 22:59 and 03:58, respectively.

To study road users' experiences of the test site, questionnaires were deployed. During the first scenario, printed questionnaires were delivered to all households in the area (about 1000 households altogether). The participants could answer either by filling out the printed questionnaire or by filling out an electric questionnaire through the link provided in the printed questionnaire. While testing for the second scenario, the questionnaire was only sent—either by mail or by e-mail—to those who had explicitly agreed to participate again in the first questionnaire, but the questionnaire was also advertised in local media; this process was repeated for the third questionnaire. In the first and second phases of the testing period, the questionnaires used were almost identical. Prior to answering the questionnaire, participants were asked to drive along the road with the test lighting during the dark period of the day. Since there was no sidewalk or cycle lane on the side of the collector road, feedback from walkers and cyclists could not be obtained. Table 1 contains the number of participants answering the questionnaires and some demographic data.

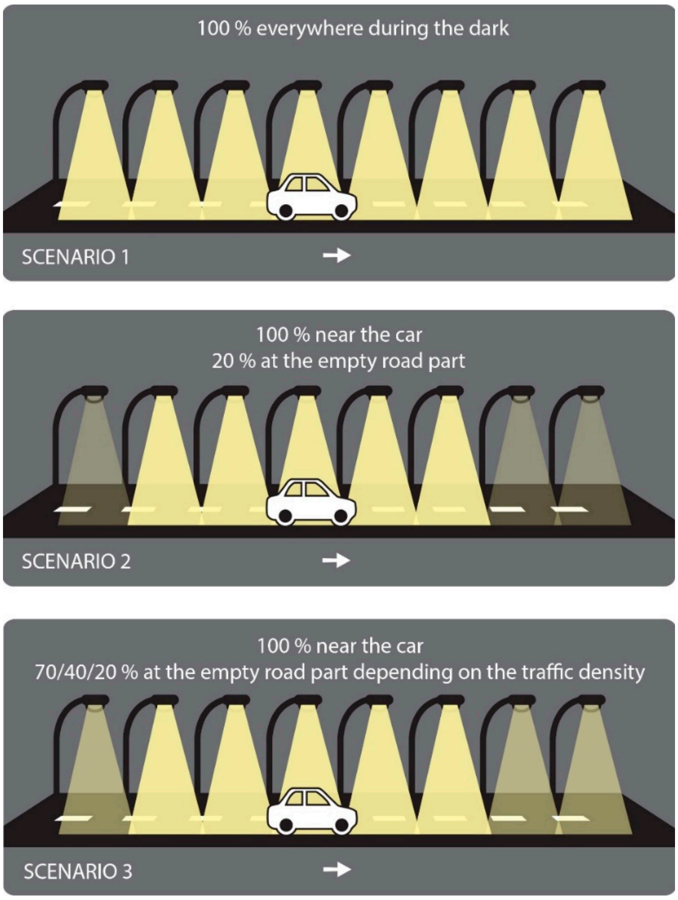

Figure 3. The lighting control principles of the scenarios. Scenario 1: Daylight level-based control, Scenario 2: Presence sensitive lighting control, Scenario 3: Presence and traffic density-based lighting control.

Table 1. Information about participants answering the first questionnaire (Q1), the second questionnaire (Q2), both the first and second questionnaires (Q1&Q2) and the third questionnaire (Q3).

	Participants	Female	Male	Age under 20–59	Age 60+	Not Local
Q1	124	54	71	97	28	1
Q2	100	41	59	82	18	1
Q1&2	94	39	55	76	18	0
Q3	52	17	35	41	11	1

To gain background information regarding our participants, we asked about their usage of the road and its prevailing conditions during the time when they evaluated the lighting. Other questions concerned their overall impressions of the lighting (pleasant or unpleasant); the experienced color of the lighting; their experiences regarding the amount of lighting on the road surface and on the surrounding environment; the experienced evenness (uniformity) of lighting; and experiences of glare. The participants were also queried on road visibility—how well they could see the road in front of them and other people moving on it or in the surrounding environment. These questions were related to those aspects of lighting quality for drivers—visual performance and visual comfort—which are the basis of lighting standards and the current method of designing road lighting [42] but expressed as questions considered to be more understandable to our participants than technical and professional terminology. Participants were also allowed to freely give personal feedback about the lighting. Moreover, participants were asked whether they had noticed any changes in the lighting during different times of the day or during their test drive. Those who answered the second questionnaire were queried on whether they had noticed any change in the lighting after the first questionnaire. Most of the questions were formulated as scales with ratings on a scale of 0 to 5, with an added possibility for open-ended qualitative commentary.

For the evaluation of the first two scenarios, the participants did not receive any information about the new lighting other than it was accomplished with LED lights and that the lighting control had been developed during that same winter and spring. This was because the objective was to gain feedback from participant experiences that were as genuine as possible, unaffected by previous knowledge. During the testing of the third scenario, the approach was the opposite. Participants received detailed information on the three different lighting control methods that had been tested in each of the scenarios. We were interested in participants' attitudes towards lighting in general, especially those toward intelligent lighting as well as the three tested control methods. Furthermore, our objective was to gain more reflective viewpoints rather than mere reports of raw experiences. At this stage, the questionnaire did not require participants to visit and observe the lighting on site due to seasonal reasons. The third questionnaire was deployed in the summer, and outdoor lighting everywhere in the country was almost completely turned off at the time because of the long daylit periods during the summer months in northern latitudes. In Salo, outdoor lighting was used only for a couple of hours in the dead of night. Thus, a site visit component at this stage did not make sense.

To disseminate information about the lighting, our team developed an urban dashboard (The City Monitor) [69] in the form of a website. In the dashboard, scalable charts, dynamic visualizations of the lighting behavior, and verbal descriptions of each lighting control method were presented. The scalable charts illustrated the average lighting and energy consumption levels.

Figure 4 illustrates the information provided in the website simulation of scenario 2. In the evaluation process, the participants could choose to answer questionnaires either in electronic or printed form. With the third questionnaire, only the electronic one had interactive and dynamic simulations, but the printed one contained the same information in picture and textual mode. The PIR sensor data of a single date (8.2.) was used for simulating lighting behavior with the three different control methods, allowing a comparison of the energy consumption [69]. The results of the comparison (presented in Table 2) indicate great energy-saving potential for both scenarios two and three.

Table 2. Results about the energy consumption simulation based on PIR sensor data of the date 8 February 2017.

The Energy Consumption at the Test Collector Road		
SCENARIO 1	**SCENARIO 2**	**SCENARIO 3**
1.1 kWh/lighting fixture	0.5 kWh/lighting fixture	0.6 kWh/lighting fixture
Energy saving as compared to Scenario 1	55%	45%

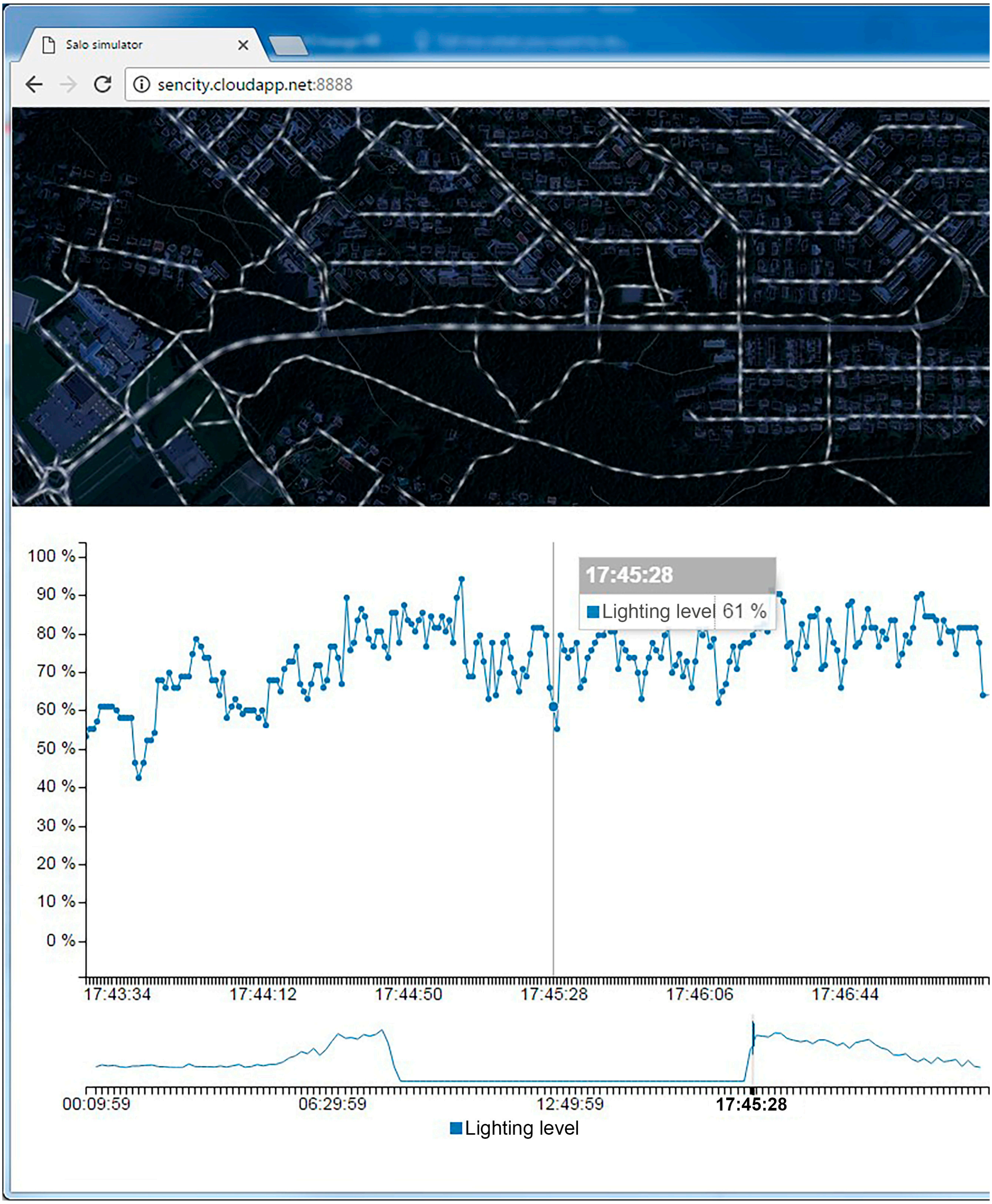

Figure 4. The participants answering to the third questionnaire, had the opportunity to gain information of the lighting scenarios visualised on the dynamic interactive web page provided through the urban dashboard The City Monitor. Users were able to select a scenario and a time on the example day. A dynamic light map simulation was shown, with the graphs of the summed-up lighting control level of all luminaires in the test area. The lower graph showed the whole day and the upper graph a selected period. The shown value was a percentage of the maximum value, also indicating the energy consumption. A screenshot of Scenario 2 (texts are translated to English).

2.2. Data Analysis Methods

The participant answers to all three questionnaires were organised into Excel sheets and checked for validity. A few participants for the first and second questionnaires were rejected based on information indicating that the participant had not been driving a car or been a passenger in a car along the test road. The answers of all accepted participants were included in the analysis and description of experiences concerning scenarios 1 and 2, the number of participants being 124 and 100, respectively, but in the statistical comparison of the two scenarios, only those participants were included who had answered both the first and the second questionnaire (n = 94). The answers to the open-ended questions were thematised into important themes and aspects, and explanatory factors for experiences were collected.

The objective was to show that the experience of presence sensitive lighting would be as positive as traditional lighting. A result of having no differences between the experiences of the two scenarios would indicate that. To test whether there were statistically significant differences between the experiences of scenario 1 and 2, the dependent samples t-test for paired samples was selected as the statistical analysis method. The data included a good sample of 94 road users evaluating both lighting scenarios, the traditional and presence sensor controlled. In the test, the difference scores (D) were used as variables, so for statistical analysis, the difference between the values of each question was calculated for every participant. As this distribution of the differences was fairly symmetrical, testing could be performed as a dependent samples t-test and corresponding 95% confidence interval calculation. If there was no difference between the sample pairs, then the mean of the difference scores would be equal to zero. Therefore, the null hypothesis to be tested was $\mu D \neq 0$.

3. Results

3.1. Traditional and Presence-Sensitive Scenarios

Figure 5 illustrates the results concerning the experiences of all participants evaluating scenarios 1 (traditional lighting, n = 124) and 2 (presence sensitive lighting, n = 100). Generally, the participants gave both lighting scenarios high scores in all the aspects which were questioned, and the scores were similar regarding both traditional lighting and presence sensitive lighting. Concerning the general appearance of lighting (0 = very unpleasant, 5 = very pleasant), the mean of the scores was 3.98 with traditional lighting and 3.94 with presence sensitive lighting. When participants were asked whether anything in the lighting disturbed them, 81% answered "no" with traditional lighting and 82% with presence-sensitive lighting. While evaluating the uniformity of the lighting on the road (0 = not uniform at all, 5 very uniform) the mean was 3.64 with traditional lighting and 3.70 with presence sensitive lighting. The lighting did not seem to cause much glare while driving, as the mean of the scores (0 = very much, 5 = not at all) was 4.14 with traditional lighting and 4.16 with presence sensitive lighting. Participants were also asked separately how well they were able to see the roadway and others moving on the road and its surroundings (0 = very badly, 5 = very well). Here the mean concerning roadway visibility was 4.16 with traditional lighting and 4.17 with presence sensitive lighting. The visibility of others moving on the road and in the surroundings was experienced as being slightly worse: the mean of the scores was 3.53 with traditional lighting and 3.77 with presence sensitive lighting. This relates also to the evaluation of the amount of light separately on the road and in the surroundings: more participants experienced that there was a sufficient amount of light on the road surface (89% with traditional lighting, 92% with presence sensitive lighting) than in the surroundings (74% with traditional lighting, 79% with presence sensitive lighting).

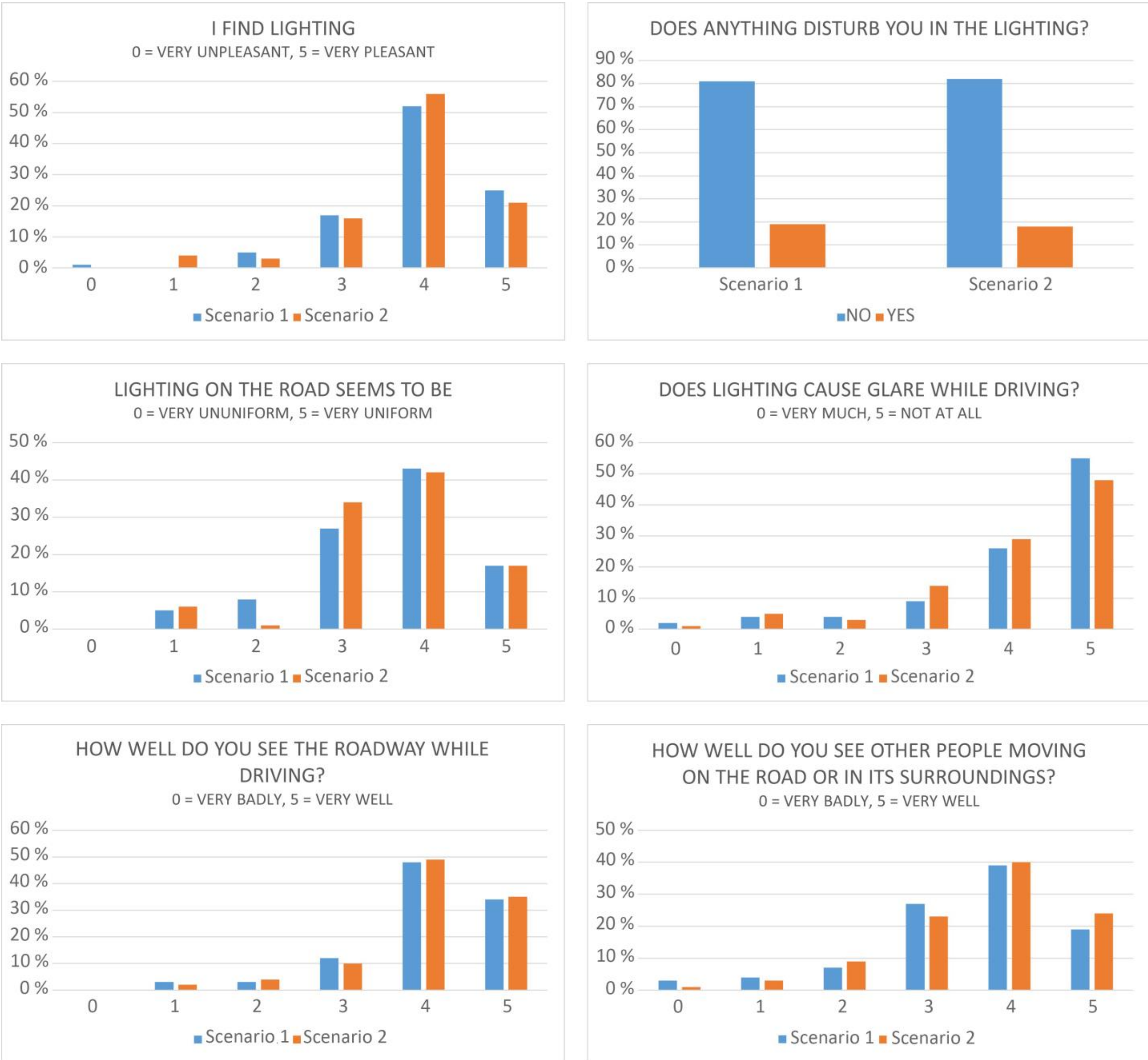

Figure 5. The comparison of participants' scores of Scenario 1 (Traditional lighting) and Scenario 2 (Presence sensitive lighting). The questions and statements are translations from the original questionnaire texts in Finnish.

The participants were given the possibility to verbally comment on their numerical evaluations, which helped us further understand the experience beyond the scores. Positive feedback was given to both scenarios regarding a sufficient amount of light (*"not too bright"*, *"a sufficient amount of light"*, *"bright"*), the tone of light (*"soft, good tone"*), and the absence of glare. However, some of the same aspects were also criticised in a few comments (*"too weak"*, *"bright LED-lights where lumen values are raised by raising the colour temperature are not sufficient for human eyes"*). Obviously, critical comments were given to the question of whether anything disturbed the participants in the lighting. These negative notions included experiences of glare (several comments), unevenness of lighting, inefficiency of lighting, costs, and the perceived redundancy of lighting. In addition, a concern regarding not having enough light by the pedestrian crossings and crossroads in general was raised.

Table 3 presents the statistics from the dependent samples t-tests conducted. For all the questions concerning (1) the appearance of the road lighting in general; (2) the evenness of light distribution on the road surface (uniformity); (3) experiencing glare when driving and; (4) experience of seeing the roadway when driving, the statistical analysis showed no difference between the compared conditions. The *p*-value in these was between 0.48–0.89 indicating that the null hypothesis had to be abandoned and the detected variation between the results is coincidental. The only exception was the question *"When driving, how well do you see the other users of the road and the environment?"* Here the results indicated a slight statistical significance in favor of the presence sensor-controlled lighting scenario: $t(94) = -2.296$, $p = 0.024$ (dependent samples *t*-test). Thus, it could be stated that the experiences of presence sensitive road lighting are at least as positive as experiences of traditional lighting, in light of the aforementioned questions.

Table 3. The results of dependent samples *t*-tests using difference scores as variables ($n = 94$): mean, standard error, 95% confidence interval and *p*-value are presented, * $p \leq 0.05$.

	Mean	SD	95% CI	*p*-Value
Appearance of the road lighting	0.043	0.775	[−0.116, 0.201]	0.596
Light distribution on the road surface	−0.064	0.878	[−0.244, 0.116]	0.482
Glare when driving	−0.021	1.136	[−0.254, 0.211]	0.856
Visibility of the road when driving	−0.011	0.796	[−0.174, 0.152]	0.897
Visibility of road users and environment when driving	−0.234	0.988	[−0.436, −0.032]	0.024 *

Respondents to both the first and the second questionnaires were questioned on whether they had noticed any differences in lighting during different times of the day. With the traditional lighting, 97% had not noticed any differences, and with the presence-sensitive lighting, 93% had not noticed any differences. There were no differences in the control method during different times of the dark time with the first two scenarios. However, depending on the time of day, the amount of traffic is altered and due to this, also the time when lighting is on at the 100% control level changes. Additionally, there were two extra questions in the second questionnaire. Firstly, participants were asked whether they had noticed any change in the lighting after the first questionnaire. Out of those respondents who had answered also the first questionnaire, 76% had not noticed any change. The comments included approximately the same number of remarks about brighter and better lighting as about dimmer lighting; however, most of the evaluations indicating dimmer lighting had added a question mark or also doubted that the reason may have been snow conditions or their own imagination. A couple of participants had noticed that a few broken luminaires had been replaced with new ones and that lights had been on during a bright day. This was probably due to the testing of the replaced luminaires. Two participants commented about noticing the dynamic dimming and brightening of lighting. One of them had been walking while making the observation. The other commented that the lighting brightens when a car is approaching. Secondly, the participants were asked whether they had noticed any change happening in the lighting while they were moving along the test road with a car. 86% of the respondents answered "no". Of those participants who reported noticing something, only four described noticing dynamic dimming and brightening. The others commented on different types of experiences, for example, they described the lighting to be better, brighter in the dark, having a more pleasant tone, or being dimmer.

3.2. Informed Opinions of All Scenarios

Here, we report on participants' answers to the open-ended questions of Questionnaire 3 which involved all scenarios. Our goal is to gain insight into what kinds of informed opinions our participants had regarding all scenarios they were presented with (scenarios 1–3).

When queried about the participants' opinions regarding scenario 1 ("What do you think of this type of lighting control method where the lighting is [continuously] kept at the same level?"), most participants considered this method to be inadequate or not sensible in some way; two participants were of the opinion that it was "old-fashioned", and three thought that it was simply "bad". Most did not consider this to be a sensible way to light since "technology enables better control without added costs", or they had concerns regarding light pollution or wasteful energy consumption. Curiously, one participant noted that they had thought this was the only possible way, but having perused our questionnaire, the participant concluded that this was "old-fashioned". Thus, it must be taken into consideration that this may very well be true for other participants as well. Even so, some of our respondents had a positive opinion of the traditional lighting scene, thinking it was "sensible and 'nice' (safe)", simply "ok" or that it "improves visibility for the elderly". However, these opinions were in the minority, with most stating that they would prefer a different type of lighting control method. Of all the participants, 28% (15 persons) wanted to have this scenario as a permanent lighting solution.

Concerning scenario 2, ("What do you think of this type of lighting control method where the lighting is dimmed where there are no passers-by?") the responses were decidedly more positive. Several participants described the lighting control method in the scenario as "good", "very good" or "sensible", and many others still gave more in-depth positive answers: "I think it's sensible to control lighting according to need"; "Good. It doesn't glare and it's better for the surrounding environment as well"; "Good idea, as long as it brightens when there's passers-by"; "Sounds logical". Several noted that it would save energy in their opinion. Some also had requirements for the system: Firstly, the control method must function reliably. Secondly, it would need to account for all types of traffic, especially at a crossroads or a pedestrian crossing. However, some clearly dissenting voices were also expressed. One notable opinion was that scenario 2 was "unnecessarily fancy". One other was concerned that it might add to feelings of unsafety. Others simply expressed negative opinions, stating that the scenario was "not good", "not nice", "suspicious" or "bad". However, these were in the minority, and unfortunately, these negative opinions were also left unexplained. Of all the respondents, 45% (24 persons) wanted to have scenario 2 as a permanent lighting solution.

For our scenario 3 ("What do you think of a lighting control method like this where the lighting is dimmed where there are no passers-by, and the lighting is also controlled by the density of traffic?"), once again, the answers proved to be mostly positive. "Best option", "I support this [idea]", "Good" and "Sounds good" were common answers. Many participants also gave more detailed reasons: "This is good too, why light up empty roads?"; "Amounts of traffic do vary a lot. It's more important to see further ahead during rush hour. Usually, light is needed more when there are more road users." One stated that it was a "Good compromise between safety and energy consumption". Again, there was an important minority of negative opinions as well. Some stated that it seemed difficult to understand, or that it was suspicious. The accurate sensing of passers-by by the system was doubted by one participant. In general, fear of faulty operation seemed to be the most prevalent negative opinion. This is understandable as a more complex system can be seen as being inherently riskier due to technical or design failure. One participant pointed out that having more "moving parts" means more maintenance, which might be costlier. One laconically stated: "As long as it works." 55% of the participants (29 persons) accepted scenario 3 as a permanent lighting solution along the road.

3.3. Results of Participation in the Design and Research of Adaptive Roadway Lighting

At the beginning of this study, we asserted the importance of citizen or user participation in the design of adaptive roadway lighting. We can see above that the inclusion of an experiential, user-focused perspective has yielded important and interesting results and implications for the design of adaptive roadway lighting. What, then, did participants think of the process they were a part of? We can approach this question through an overall interpretation of the open-ended answers to the questionnaire, and also more specifically through the final question; which consisted of free commentary in response to the question: *"Is there anything else you would like to say?"*. This question was meant to engender reflection and capture any remaining thoughts, ideas, and opinions that the participants might still have. These opinions are especially important since they were not specifically prompted, and as such, they represent points that were in some way salient for our participants. In the questionnaire, we received 27 open-ended answers to this final question. Some of the comments we received here were requests for a certain kind of lighting (especially for highlighting the pedestrian crossing with lighting), but many were a kind of meta-commentary about participation or adaptive roadway lighting. Next, we will briefly discuss these two types of answers to the question.

On participation, our respondents expressed unanimously positive opinions, for instance: "It was a great experience to participate and influence the lighting in my own area. Thank you" and "All of this was interesting, I'm glad I joined". While the majority did not comment on the participatory process at all, no one expressed a negative attitude toward participation. This is unsurprising in a self-selected group, and unmotivated participants had likely given up—at this point, 51 original participants remained out of the initial 124 that had filled out Questionnaire 1. However, we deemed this to be a surprisingly large number of people. Only one person who filled out Questionnaire 3 was new to the process; others had filled out all three. Thus, it is important to note that there were genuinely interested individuals who were eager to have a say in the development of their environment and its lighting, and who were prepared to spend their time on three separate occasions to do so. These interested individuals played an important part in supplying researchers with local and user-centered points of view, as can be seen in the results presented in this paper.

On adaptive roadway lighting, many also expressed an unprompted positive attitude towards developing the environment and/or adaptive roadway lighting in general, for example: "*Thank you for developing the lived environment!*" and "*I hope the technology is durable and we can continue to keep developing it*." "*This is a good topic [for research] since lighting spends a lot of energy nationally and globally*." "*Energy efficient lighting is a good thing*". One also expressed happiness about the city of Salo specifically being at the forefront of novel technology adoption. It could be noted here that a Nokia mobile phone factory was located in Salo for many years, playing a central part in the contemporary development of the city. Prior to this, the city was the home of the Finnish radio and television manufacturer Salora from 1936 onwards [70,71].

Overall, in Questionnaire 3, participants' answers to other questions may also be interpreted from the point of view of participation. In the open-ended questions, participants overwhelmingly highlighted safety and functionality issues, and this is to be expected in the context of roadway lighting. It could be interpreted that it might be important for the participants to be able to have a say in these issues specifically.

In general, participation also enabled our participants to receive information and learn about (adaptive) roadway lighting. Participants reacted positively to gaining new information also through a rated question ("How important do you consider it that there is information available about lighting and its function in the urban environment?"): most participants rated this 4 (25 participants or 47%) or 5 (15 participants or 28%) on a scale of 1–5 where 5 was the highest score.

Interestingly though, most participants estimated that gaining information about the lighting did not influence their experience of the lighting (33 participants or 62% thought this way). This illustrates the limits of participant-gained information, as one of our main results (that most of the drivers did not notice any change happening in lighting while they were moving along the test road with a car in scenario 2) indicates the opposite. Thus, participant studies should be carefully constructed to take the limits of experiential knowledge into account. In fact, this gap between subjective participant experience and notions, and objective, external viewpoints should be carefully studied in the context of adaptive roadway lighting.

4. Discussion

In the following, we discuss our findings in light of earlier research. The discussion is thematically divided into a section on experiences and informed opinions and a section on participation in a smart city, and it includes reflection on the limitations of our study and further research suggestions for both themes.

4.1. Experiences and Informed Opinions

The results of this real-world case study in Salo indicate that, in our study, drivers' experiences of presence sensitive roadway lighting were at least as positive as the experiences of traditional, uncontrolled lighting concerning many factors which are essential from the perspective of traffic safety and comfortable driving experience [42,45]. These included the experienced uniformity of lighting on the road surface, the experience of glare, and the visibility of the road while driving. In addition, presence sensitive lighting was experienced as being as pleasant as traditional lighting. In the statistical testing of the results with dependent samples t-tests no statistically significant difference between the two tested lighting scenarios was detected. However, concerning the visibility of other people moving on the road and in the surroundings, the test results indicated slight statistical significance and better results with presence sensitive lighting. One explanation for this surprising result might be the experienced focus effect as the illuminances were higher near the driver than in the far distance along the road. The results of the recent study of dimmed, static road lighting and car headlights [48] interestingly relate to this and open new research questions and potential applications for presence sensitive and intelligent lighting.

When participants were asked specifically about negative experiences, almost the same percentage of participants (19% with the traditional lighting, 18% with presence sensitive lighting) reported that something disturbed them. Interestingly, most of the drivers (at least 86%) did not notice any dynamic change in lighting while driving along the test road. This indicates that even though a presence sensitive road lighting environment—being dynamically controlled—lacks de-facto stability, it can possess, when designed with care, experienced stability which makes the driving experience comfortable. When informed about the tested lighting strategies, most of the participants (72%) would prefer either one of the intelligent lighting modes to be the permanent lighting solution. The attitudes towards intelligent lighting were generally positive: it was deemed to be a wise and modern solution—saving energy and costs, and providing lighting when needed.

Limitations and suggestions for further studies: While the results are extremely encouraging and would suggest the feasibility of presence sensitive lighting as a safe solution for roadway lighting, we acknowledge that there are limitations to our study, and more research about the actual effects is needed. Our research evaluated the experience of the drivers as they reported them—not the influence of the lighting conditions on driving behaviour or the drivers' actual ability to detect pedestrians, for example. As suggested in the studies [46,47], the case might be that even though the drivers experience that they see well both the roadway and other people moving on the road or in its surroundings as indicated in the answers, they might not realize that their focal vision is reduced. A longitudinal study with the analysis of the data of potential accidents on the roadways with presence sensitive lighting would be needed. Additionally, our study was an in-the-wild user study, which operated in a naturalistic, real-world setting and aimed to capture everyday life user experiences. There is, however, a need for more controlled studies, as well, where factors such as weather conditions and traffic volumes would be controlled.

Our study and the applied lighting control method, which was based on the measurement of traffic density, interestingly relate to the adaptive lighting methodology proposed in [44]. Following their concept, where roadway conditions influence the active selection of the system's lighting level, presence sensitive lighting could be developed further to react to detected conditions of the road, such as a snow cover on the roadway. In northern Finland, for example, this could lead to substantial savings in energy and costs, as lighting could be intelligently dimmed during the period of snow cover that lasts for several months, and consequently reduce the amount of light pollution in the form of sky glow, caused by reflected light.

As stated, the focus of our study was on drivers' experiences; thus, our questionnaires did not include questions concerning how presence sensitive lighting was experienced as seen from inside buildings through windows. Most parts of our test site's collector road were not directly adjacent to housing sites, as there was a zone of forested area in between. Furthermore, the adaptive behaviour of the lighting employed soft ramps up and down, and therefore it was estimated by the researchers to be experienced as pleasant. This aspect of the influence of dynamically adaptive lighting behaviour on the experiences in neighbouring buildings should be tested in a denser housing area setting.

4.2. Participation in a Smart City

As previously argued, adaptive roadway lighting is an example of a smart city technology. Through this framing, we can connect the research on adaptive lighting with the research on smart cities. From this point of view, we are reminded by the body of work that has been produced on smart cities and the importance of citizen participation in the research and design of design agendas, infrastructures, and services. This study represents a step forward in the study of adaptive roadway lighting from an experiential and participatory point of view. However, more studies with various levels of participation should still be conducted—from feedback studies to fully co-creative approaches. Furthermore, various stakeholder groups that differ in age, gender, ability, etc., should be invited to participate.

Participants' experiences were a central source of knowledge for our study, and also show that there indeed are interested user-stakeholders that are motivated to use time and effort to have a say in the design and implementation of adaptive roadway lighting. The eager reception of information would support the notion that roadway lighting should be studied through experiential and participatory methods since participation can be seen as a process of mutual knowledge production and learning, and learning new information was seen positively. Thus, participatory methods could be used to disseminate information about roadway lighting.

Yet our results also are a reminder of the importance of expert viewpoint and objectively measurable testing—our participants were not able to accurately ascertain what was truly happening with the adaptive lighting scenarios through on-site experience, and despite this, most did not think that receiving information about how the lighting worked had any impact on their assessment of the scenario, which we interpret as not being credible. Thus, participation is important from the point of view of ethics and knowledge production; but expert knowledge and further testing are still needed to interpret the knowledge, and ultimately, to ensure that adaptive lighting is applied in a safe, responsible, and socially sustainable manner.

Similarly, smart city literature and technology research in general often rightfully critique and warn of the loss of individual privacy in the implementation of data-driven technologies. [72] These societal problems should also be addressed by smart city and adaptive lighting research. Importantly, our test sites did not include any data collection of individuals or their vehicles, nor was this deemed necessary for the successful operation of presence-sensitive roadway lighting. This points to the possibility of applying algorithms ethically in the area of adaptive roadway lighting.

Overall, adaptive roadway lighting may be a fruitful area of research for sustainable smart city research in general where substantial progress could be made toward the goal of fostering "economic development while conserving resources and promoting the health of the individual, the community and the ecosystem" [58]. As roadway lighting is a center of energy consumption globally, the implementation of adaptive lighting technologies represents a possibility to reduce energy use and gain financial benefits while improving human and non-human experiences by reducing light pollution and providing more purposeful illumination.

5. Conclusions

In our exploratory, real-world study, drivers' experiences of presence sensitive roadway lighting were at least as positive as the experiences of traditional, uncontrolled lighting concerning many factors which are essential from the perspective of traffic safety and comfortable driving experience. These results point towards the potential feasibility of this technology from a user experience perspective, as the experienced stability of the lighting was unaltered in the tested scenarios; importantly, it also highlights the need to study adaptive roadway lighting further, especially through confirmatory studies in controlled settings. Additionally, the results also point toward the need for research supporting the formulation of novel, supplementing design factors and parameters for road illumination in order to assure the overall quality of the new design conceptions of adaptive road lighting. We call for further research into adaptive roadway lighting to ascertain the usability, safety, and sustainability of such applications in differing smart city environments.

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